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THE JOURNAL OF SOIL SCIENCE

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THE SCEPTICAL SOIL CHEMIST[1]

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A PRESIDENTIAL Address provides an opportunity for considering the aims and methods of our subject. Soil science concerns matters on which knowledge and tradition have been built up since the beginnings of civilization and which are of lively concern to vast masses of people. In so far as we are able to think out and explain the 'tactics and strategy' of our science, we may be able to improve our own work and, at the same time, to obtain better facilities for advancing our subject and its practical applications. Further, we may help to correct some of those misunderstandings about the nature of science which are apt to arise from the dogmatic presentation of many textbooks, the popular exposition of abstruse subjects, and many varieties of 'science-fiction'.

For a modern statement of the general 'tactics and strategy' of science, addressed primarily to non-specialist students and laymen, I should like to refer to a recent book *Science and Common Sense* by Professor J. B. Conant, President of Harvard. The emphasis throughout is on the sceptical approach to science and the distinction between the empirical experimentation of the workman and the scientific experiment directed towards testing the consequences deduced from speculative general ideas and intended to contribute towards establishing a broad conceptual scheme. Professor Conant's own definition of science is: 'an interconnected series of concepts or conceptual schemes that have developed as a result of experimentation and observation and are fruitful of further experimentation and observation'. Professor Conant stresses the point that since the rise of scientific societies in the seventeenth century science has become a self-propagating social phenomenon. In discussing the relation between science and technology he introduces the term 'degree of empiricism' to indicate the extent to which our knowledge can be expressed in terms of broad conceptual schemes and illustrates it by a scale in which the work of a cadastral surveyor might have a zero degree of empiricisim, because all his methods and tools are derived from well-developed theories, and that of a hotel chef might be ranked as practically 100 per cent. empirical. On this basis one may consider science as an attempt either to lower the degree of empiricism or to extend the range of theory. I think that one might make an agricultural parlour-game by attempting to place various agricultural systems on Professor Conant's scale of empiricism. Among the least empirical there might be the pineapple industry of Hawaii, the irrigated cotton of the Sudan Gezira, the almost continuous cotton of the Mississippi Delta, the vegetable growing of Florida, the bulb growing and the newly reclaimed polders of Holland. Many of these highly productive systems have been developed on inherently poor soils where there were facilities for

[1] Presidential Address, presented at the Annual Meeting, Royal Agricultural College, Cirencester, September 1952.

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controlling water-supply. Some of them have been described as 'precision farming', but few of them could be used to illustrate so-called 'principles of good husbandry'. Systems of mixed farming are inevitably more empirical because it is difficult to analyse complex interlocking systems, and it is necessary to rely on many kinds of skill acquired through long experience of stable but not very productive systems. In a world threatened with increasing shortage of food and raw materials there is much promise in the success of intensive systems of production established by skilled practical men working with specialists in various branches of agricultural science.

Soils and Agriculture in Antiquity

To help us to appreciate the parts played by accumulated knowledge, intuitive interpretation, and scientific investigation, I think that it is well to recall that many vital steps in agriculture were taken in prehistoric times and that several of the great thinkers of antiquity arrived at conclusions not markedly different from those often put forward nowadays in the name of science.

Classical antiquity provides a fund of sound information on agricultural practices. The relevant parts of Vergil's *Georgics* on using leguminous crops before cereals, burning stubbles, and testing soils by profile pits and water extracts are so well known that they need not be quoted here. Columella, too, gives much shrewd practical advice, though bizarre items are apt to creep into his recommendations. Thus, in describing methods for making compost, he suggests driving an oak stake through the middle of the heap to keep off the dreadful serpent.

The following quotation from Plato's last and unfinished work *Critias*, written about 350 B.C., provides an excellent example of interpretation in geomorphology and shows that Plato had a sound grasp of denudation, sedimentation, soil erosion, and the storage of water in soils and rocks protected from run-off.

> Contemporary Attica may accurately be described as a mere relic of the original country, as I shall proceed to explain. In configuration, Attica consists entirely of a long peninsula protruding from the mass of the continent into the sea, and the surrounding marine basin is known to shelve steeply round the whole coastline. In consequence of the successive violent deluges which have occurred within the past 9,000 years (the interval which separates our own times from the period with which we are dealing), there has been a constant movement of soil away from the high altitudes; and, owing to the shelving relief of the coast, this soil, instead of laying down alluvium, as it does elsewhere, to any appreciable extent, has been perpetually deposited in the deep sea round the periphery of the country or, in other words, lost; so that Attica has undergone the process observable in small islands, and what remains of her substance is like the skeleton of a body emaciated by disease, as compared with her original relief. All the rich, soft soil has moulted away, leaving a country of skin and bones. At the period, however, with which we are dealing, when Attica was still intact, what are now her mountains were lofty, soil-clad hills; her so-called shingle-plains of the present day were full of rich soil; and her mountains were heavily afforested—a fact of which there are still visible traces. There are mountains in Attica which can now keep nothing but bees, but which were clothed, not so very long ago, with fine trees producing timber suitable

for roofing the largest buildings; the roofs hewn from this timber are still in existence. There were also many lofty cultivated trees, while the country produced boundless pasture for cattle. The annual supply of rainfall was not lost, as it is at present, through being allowed to flow over the denuded surface into the sea, but was received by the country, in all its abundance, into her bosom, where she stored it in her impervious potter's earth and so was able to discharge the drainage of the heights into the hollows in the form of springs and rivers with an abundant volume and a wide territorial distribution. The shrines that survive to the present day on the sites of extinct water-supplies are evidence for the correctness of my present hypothesis.

The translation is by A. J. Toynbee and is taken from a chapter entitled 'The Stimulus of Hard Countries' in volume ii of his *Study of History*. Toynbee argues that when the soils of Attica were lost by erosion her people turned to cultivating olives and had therefore to learn how to use raw subsoil clays for jars and pottery, how to establish a merchant navy to carry the oil abroad and bring back grain, and how to build with stone in place of timber. This interpretation of the rise of Athenian power and art is diametrically opposed to the guesses of some soil conservationists, who have asserted that the decay of Greek and other Mediterranean civilizations can be ascribed to soil erosion through over-cropping soils cleared from forests. Such a clash of opinions illustrates the difficulty and the danger in attempting to apply our knowledge of soils to problems remote in time or space.

It has often been suggested that the Greeks contributed little to science because they left their agriculture and industry largely to slaves. Plato's philosophy, with Aristotle's logic and systematic treatment of common-sense descriptions of natural phenomena, fixed the general pattern of thought and discussion for nearly 2,000 years, until the great sceptics of the sixteenth century in Italy and the seventeenth century in north-west Europe began to make experiments and detailed observations, often with new instruments, to test their speculative thinking and deductive reasoning. Some relics of Platonic and Aristotelian methods may still be influencing our treatment of soils. The late Professor G. W. Robinson told us that the way in which some of us spoke of 'podzol' or 'chernozem' reminded him of a Platonic 'Idea' of a 'podzol' or 'chernozem' laid up in some heavenly monolith.

Soils and Agriculture in the Seventeenth Century

The wonderful outburst of scientific investigation in the seventeenth century has often been illustrated by the works of Galileo, Newton, and Harvey, but for the soil chemist the work of Robert Boyle is of special interest. In 1646, at the age of 19, he was already writing to his tutor about his studies in 'natural philosophy and husbandry according to the principles of our new philosophical colledge that values no knowledge but as it hath a tendancy to use'. Later he wrote a book, *Of the Usefulness of Experimental Natural Philosophy*, to show how 'the good of mankind may be increased by the naturalist's insight into trades'.

Boyle's *Skeptical Chemist*, published in 1661, is much better known than his other books. His object was to attack the evidence for the

Aristotelian doctrine of four 'elements'—earth, air, fire, and water—and the alternative one of three 'principles'—salt, sulphur, and mercury. The Aristotelian advocate in the discussion relies mainly on the 'obvious and easy analysis' afforded by the demonstration that a piece of green wood burning in a chimney at once shows the flame, smoke, water, and ash corresponding to the four elements. Boyle sees no evidence that fire resolves bodies into simpler ones or that there are only a few elements. He outlines definitions of elements and compounds in terms of the properties they exhibit when subjected to specific tests, but he could not get very far in applying his definitions.

Sprinkled through the rather tedious discussions of the *Skeptical Chemist* are many paragraphs of special interest to soil chemists. Thus there is an account of van Helmont's famous pot experiment in which in 5 years a willow-tree increased in weight by 164 lb. whilst only a couple of ounces of soil were lost from the pot, thus indicating that the whole substance of the tree had been derived from water. Boyle had independently caused his gardener to make two similar single-year experiments. In one, with a kind of squash, there was no loss in weight; in the other, made with cucumbers several years later, about a pound and a half of soil were lost. The gardener thought that the missing earth was not in the cucumber but in 'the dust (and the like) wasted'.

I think that if Boyle had been present to watch the actual separation of roots and soil he would have found, as many of us have since found, that it is a difficult operation to carry through quantitatively. He might then have been as sceptical of the results and interpretation of van Helmont's pot experiments as he had been of much of van Helmont's other work. It has happened many times in the history of agricultural experimentation that the results obtained were consistent with the hypothesis leading to the experiment, but that some unsuspected factor had been overlooked. Boyle suggested that future experiments on these matters might be made with several tobacco plants grown in a single pot, but he himself preferred to make 'shorter and more expeditious' trials in water culture. Many later workers have been driven away from soils to simpler systems because soils are particularly troublesome to handle in pots and laboratory apparatus.

From the Middle Ages until well on into the seventeenth century in Europe and almost to the present time in parts of China, wars depended on gunpowder made from saltpetre prepared through nitrification in natural soil, old buildings, or special beds. Boyle knew from 'boylers of saltpetre' that 'if an earth pregnant with nitre be deprived, by affusion with water of all its true and dissoluble salt, yet the earth will after some years yield them saltpetre again . . . whence it may appear, that the seminal principle of nitre latent in earth does by degrees transform the neighbouring matter into a nitrous body'. It was a great advance in bacteriology to replace Boyle's 'seminal principle of nitre' by *Nitrosomonas* and *Nitrobacter* and to ascertain the strange biochemical behaviour of these micro-organisms. Perhaps, before long, bacteriologists and biochemists may be able to make these organisms behave in culture solutions in much the same way as they do in soils, manure heaps, sewage

works, and nitre beds. In the meantime the soil chemist in his more sceptical moments may wonder whether what is now known about the mechanism of nitrification has helped him very much in interpreting agricultural experience and whether some of his colleagues are wise in postponing field investigations on the effects of nitrogen fertilizers until microbiologists have explained the natural fluctuations in the soil's nitrate supply.

In accordance with the prevailing interest in mechanics, Boyle wrote:

> I am apt to think that men will never be able to explain the phenomena of nature, while they endeavour to deduce them only from the presence and proportion of such or such material ingredients, and consider such ingredients or elements as bodies in a state of rest. . . . For 'tis by motion that one part of matter acts upon another; and 'tis, for the most part the texture of the body upon which the moving parts strike, that modify the motion or impression, and concurs with it to the production of those effects which make up the chief part of the naturalist's theme.

This paragraph may still serve as a warning to soil chemists on the dangers of relying on isolated analytical determinations on soils and plants. The paragraph may also be taken to anticipate some aspects of modern theories of ionic exchange, catalysis, and enzyme action.

Boyle was an active member of the Invisible College which preceded the formation in 1662 of the Royal Society, of which he was a founder member and later President. He drew up elaborate programmes for surveys. His *General Heads for a Natural History of a Country*, published in 1665, is a check-list for explorers. One of its items is: 'by what particular arts the inhabitants improve the advantages and remedy the inconveniences of their soil'. It may have been largely under Boyle's influence that in 1665 the Georgical or Agricultural Committee of the Royal Society issued 'certain heads of enquiries concerning agriculture to be distributed to persons experienced in husbandry'.

A few of the questions listed for 'arable grounds' were:

> 1. The several kinds of soil in England supposed to be either sandy, gravelly, stony, clayey, light mould, heathy, marish, boggy, fenny or cold weeping ground: what is the soil of each country and how prepared for arable?
>
> 2. What peculiar preparation each soil undergoes for each kind of grain; with what kind of manure they are prepared; when, how and in what quantity is it laid on?
>
> 5. How, and for what productions, heathy grounds may be improved?
>
> 6. What ground has marl? . . . What time of the year it is to be laid on? How many loads to the acre? . . .
>
> 10. What quantity of each kind [of grain] is sown on the statute acre? And in what season of the moon and year?
>
> 15. Upon what occasions young corn is cut or fed in the blade; and what are the benefits thereof?

No reports appear to have been published on the findings, but a recent account (Lennard, 1932) mentions that replies are known to have been received only from Yorkshire, Kent, Devon, Cornwall, and parts of Dorset and Gloucester. In more than one way the 1665 inquiry resembles the Survey of Fertilizer Practice, which has been undertaken since 1942

by the Advisory Chemists of England and Wales in association with Rothamsted statisticians.

In a paper published in *Philosophical Transactions* in 1673 Lister 'was of opinion, that by examining the earth from the surface downwards, as often as opportunity offered, a pretty just theory might be formed of its contents in general; for it appeared from his own observations, that upper natural soils infallibly produce the same internal minerals and materials. He has thrown out a hint to every nation for extending this useful knowledge, by advising that a soil or mineral map should be made, properly distinguished into countries, and enriched with observations for general use, arising from remarks on the bounds and produce of every particular soil.'

In 1676 the Royal Society sanctioned the publication of John Evelyn's *Terra, a Philosophical Discourse of Earth relating to the Culture and Improvement of it for Vegetation and the Propagation of Plants*. The first sentence of this book accords very well with Professor Conant's definition of science. Evelyn says he was commanded by the President and Council of the Royal Society 'to entertain this Illustrious Assembly with something which, being either deduced from or leading to, Philosophical Experiment may be of real use'.

I shall refer only to two or three isolated points from Evelyn's book. In his introductory pages Evelyn says:

> Those who have written *de Arte Combinatoria* reckon up no fewer than 179,001,060[1] different sorts of Earths; but of all this enormous number, as of all other good things, it seems they do not acquaint us with above eight or nine eminently useful to our purpose; and truly I can hardly yet arrive at so many.

After listing all the various wastes available as manures Evelyn argues:

> we are not yet to imagine that any of them are therefore profitable and good, because they retain a heady scent, are hot, moist, rotten and slippery, fat or unctuous and the like, which are all qualities that, alone and of themselves, effect little till they are corrected and prepared. The next thing is, skilfully to apply what we have prepared; and this indeed is a difficulty worthy the heads, as well as hands, of the profoundest philosophers, since it requires more than superficial knowledge and penetration into causes. That the secret we inquire after, is some vegetable salt or matter, I suppose is generally agreed . . . but whether it be accidental or essential, corporeal or more spiritual, principal or organical. . . . I leave to those who effect to wrap up *easy* notions in *hard* and uncertain terms, whilst the things would be of use to the philosophical husbandman, were they reduced into just classes, for the better discriminating of the several composts; as which of them most abound in nitrous or urinous parts; or which partake of the nature of our crude common salts, and Kali's mineral, or other. This would enable us to pronounce *where* and *how* we may apply them with safety and success. . . . I firmly believe, that were saltpetre (I mean factitious nitre) to be obtained in plenty, we should have need but few other composts to meliorate our ground. . . .

[1] This number contains at least one large prime, which is unlikely in any system of enumerating possible factors. I have wondered whether it might be a miscopying of 479,001,600 (factorial 12).

Theory and Method

I have given this rather long list of quotations from seventeenth-century writers to show how far they could go in speculative thinking and deductive reasoning and in drafting research programmes and projects. It may help us in considering the broader aspects of our own work to ask why these early inquiries had so little effect on agriculture or industry. Boyle and his colleagues clearly lacked suitable general concepts and experimental techniques for attacking difficult problems which they could appreciate but could express only in vague terms, not amenable to measurement. The necessary 'climate of opinion' was lacking. The difficulties facing them in chemistry may perhaps best be appreciated by recalling that Newton devoted much more of his working life to chemistry, in which he appears to have achieved little, than to mathematics and physics, which he transformed. So long as gases were regarded as modified airs (e.g. air with a smell) and there were no known means of preparing, handling, and testing separate gases, it was impossible to understand even the rudiments of combustion, fermentation, respiration, and photosynthesis. These developments had to wait for more than a century. The story of the search for the principle of vegetation has been admirably told in Sir John Russell's *Soil Conditions and Plant Growth* in an introductory chapter, which has fortunately been preserved unchanged through all the subsequent editions.

The delay in finding suitable techniques for agricultural experiments and surveys was far greater than for chemistry and plant physiology. Reliable and progressive methods of field experimentation have been devised only within the last 30 years. Adequate methods for making agricultural surveys have been developed so recently that their potentialities are not yet widely appreciated. Agricultural surveys of the kind proposed by Robert Boyle, and often attempted subsequently, failed because they fell between the two extremes of aiming at a complete census or of relying on the subjective impressions of individuals. It is of interest in this connexion to note that the most authoritative treatment of modern methods of survey, *Sampling Methods for Censuses and Surveys*, by F. Yates, prepared at the request of a United Nations Sub-Committee to assist in the execution of the projected 1950 World Census of Agriculture and the 1950 World Census of Population, contains a number of illustrative arithmetic examples taken from the Survey of Fertilizer Practice in England and Wales. This circumstance illustrates how an investigation into an urgent practical question may, provided it is scientifically planned, yield raw material for valuable theoretical advances in addition to supplying answers of known precision to the immediate question. The alternative method of surveying fertilizer practice by collecting vast numbers of individual opinions from users has been tried several times in the United States, but it is doubtful whether it has yielded much more than propaganda material.

Lack of precise techniques with appropriate theoretical backgrounds was not, however, the sole or perhaps even the prime obstacle to be overcome before the experiments and surveys proposed by Boyle,

Evelyn, and their colleagues could be undertaken. Experiments of quite simple design would have given striking contrasts between some of the treatments they discussed, though the experiments would, inevitably, have been laborious and expensive. As Boyle observed about his proposed pot experiment with several tobacco plants, 'everybody has not conveniency of time and place for this experiment'. The Royal Society soon ran into serious financial difficulties. Hooke and, later, Papin were appointed 'curators of experiments', but nearly two centuries had to pass before the Society, its numerous successors in special branches, individual enthusiasts, and finally Government Departments were prepared to provide funds for professional experimenters, observers, and surveyors who could obtain the data and make the personal contacts required for linking theoretical work to practical conditions in agriculture.

At the present time there can be no soil survey in a tropical country until the local government or some other body, such as the United Nations, appoints or seconds suitable men for the job. The making of such appointments depends on how far the administrators concerned are satisfied with the returns likely to be secured from this investment by comparison with those from many other promising alternatives. The choice will be influenced by the kind of advice they receive about the tactics and strategy of the particular branch of sciences involved. Similar difficulties arise everywhere in connexion with field experimental work on soil fertility questions. Some body of laymen or specialists in other fields of science must decide what funds are to be made available and then an individual or group of workers must strike a balance between conflicting ways of spending the money. F. Yates has recently made an important contribution by formulating this problem in general terms and offering a first approximation to a solution in a paper entitled 'Principles governing the Amount of Experimentation in Developmental Work'. He took an example from a branch of agriculture in which both theory and practice were well developed and for which some experimental data were to hand, viz. the manuring of sugar-beet in Britain. He showed how the optimal annual number of field experiments might be evaluated by equating their estimated cost (ignoring overheads) to the aggregate loss from failing to manure the whole crop at somewhere around the most profitable level.

Clearly the aggregate returns from any fertilizer will be increased by adjusting the dressings in accordance with known characteristics of the various soils, as is, of course, already done to a large extent by skilled farmers. The task of the soil chemist is not merely to distinguish responsive and unresponsive soils but to make recommendations demonstrably better than those likely to be made by the farmer and his other advisers. The task is difficult, but systematic experimentation could lead, first, to general recommendations for each crop and region and, then, to appropriate adjustments for changing prices, past treatments, and information derived from soil surveys and soil analyses. An approach somewhat along these lines contributed to the success of the ploughing-up campaign and fertilizer rationing scheme of the 1940's in the United Kingdom.

Series of field experiments are essential for checking the local value of various methods of soil analysis for advisory purposes and for improving these methods. In Africa and in some other parts of the world, vast numbers of soil samples are being analysed before there are any relevant field experiments or even before suitable techniques have been found for using fertilizers in field experiments.

There are many important subjects in soil science for which we are not yet ready to contemplate large series of field experiments and have, therefore, to be content with finding ways of conducting pilot experiments. This is particularly true for questions concerning long-term effects. It has been known for a century that soluble phosphates are held almost completely in the top foot or so of soil. It is well known that fresh applications of soluble phosphates applied at an appropriate time and place commonly give better results than residues from similar amounts applied a few years earlier. This may suggest that the residual benefits are small, but there is farming experience and a little experimental evidence to suggest that these small residual effects of phosphates may nevertheless continue for long periods and that repeated heavy dressings may provide a useful, though somewhat extravagant, long-term investment. There is, however, little evidence on the residual effects of phosphates on different kinds of soil.

Some of the most difficult problems in soil science concern the ways in which alternative systems of husbandry influence soil fertility. Practical observations are difficult to interpret because the variables are inevitably correlated and the results depend very much on the skill and resources of the farmer. In countries with considerable total rainfall or with occasional heavy storms the vital step is to prevent soil erosion and to ensure that the water quickly enters the soil. Recently ploughed-in leys provide these conditions, but they also improve the soil in many other ways, e.g. by fixing nitrogen and by reducing some of the common weeds, pathogenic fungi, and pests of arable crops. In countries of low rainfall or liable to seasonal droughts the leys may dry the subsoil excessively and it may then be safer to rely on stubble mulching, disking, and other cultural methods to protect the soil surface and retain water, and on fertilizers to supply extra nitrogen. Experience of enterprising practical men in exploiting new machines shows that there are vast potentialities in unorthodox systems of crop rotation. There is an urgent need in many countries for field experiments testing and analysing some of the factors influencing soil fertility in contrasted rotations.

Old and Ambiguous Terms

One of the recurrent troubles in soil science arises from the circumstance that its objectives, methods, and findings have to be described and discussed at many different levels of abstraction and thus in many different kinds of language. Forty years ago Sir John Russell, in the preface to the first edition of *Soil Conditions and Plant Growth*, warned us of the dangers:

> Illustrations used in farmers' lectures to drive home some important point to an audience before whom lucidity is above all things necessary have acquired the force

of established facts; whilst statements and sometimes even substances, have come to be believed in for no better reason than that people have talked a great deal about them.

We may have improved in the interval, but a few of our conventions would repay reconsideration. The introduction of the young agricultural student to the inherently difficult chemistry of soils, plants, and animals is rendered a little harder by expressing analytical results in terms of P_2O_5 and K_2O. The teacher may have to explain the retention of these archaic terms to familiarize his students with advertisements and invoices for fertilizers and feeding-stuffs, but the trades concerned and those who frame official regulations keep to the old units, because they are still the only ones in common use and there is no insistent demand for a change.

Misunderstandings may arise from such apparently simple expressions as 'plant food', 'available phosphoric acid', and 'lime requirement'. Farmers, agricultural officers, and specialists in other branches of science may be misled if they fail to realize that our estimates of 'available nutrients' in soils, fertilizers, and manures express data obtained by analytical methods devised for certain specific and restricted purposes. The methods are conventional and the terms in which the results are expressed should not be taken literally.

I should like to give an example of such a misunderstanding within my own experience. After the failure of early attempts by the Forestry Commission to establish conifer forests by direct sowings on a poor highly podzolized soil under *Calluna* at Wareham in Dorset, the late Dr. M. C. Rayner, an authority on mycorrhiza and an expert gardener, showed that excellent trees could be grown by sowing the seeds in patches heavily dressed with certain composts. Dr. Rayner ascribed her dramatic successes to the effect of certain organic substances in the composts in activating appropriate classes of mycorrhizal fungi in the soil. She carried out a pot experiment to compare composts with 'equivalent amounts of lime and available nitrogen, potash and phosphoric acid'. She found that the composts gave much better plants and concluded that 'increase in the supply of available nutrients plays a relatively insignificant role in the maintenance of healthy and vigorous growth that follows addition of composts to the soil'. If this finding could have been substantiated and extended, it would have indicated a serious defect in our current concepts on crop nutrition, but much depended, as it so often does, on the exact way in which the experiment was conducted and, in particular, on the precise meaning of the tricky words 'equivalent' and 'available'. I noticed that the fertilizer dressings had been calculated from earlier estimates of 'available nutrients' made by the Mitscherlich pot experiment technique at the Macaulay Institute for Soil Research. The fertilizers in Dr. Rayner's pot experiment supplied much less N, P, K than the composts and it was not therefore surprising that the ferilizers gave smaller plants. The experiment thus showed little more than that two workers using different techniques, crops, and materials in different places and years failed to agree in their estimates of the 'available nutrients' in certain types of compost. The experiment

gave no information about specific effects of organic compounds in compost.

Since 1945 we have had the opportunity of working with the Research Branch of the Forestry Commission on nutrition problems in forest nurseries, some on very poor acid soils. It took 2 or 3 years to develop a suitable plot technique and to discover how to apply the common water-soluble fertilizers safely and effectively to seedbeds, because there was little or no previous experience on these matters. We found that we could raise at least as large seedlings and transplants with soluble fertilizers as with composts, and we failed to find any consistent difference in forest behaviour of plants of similar size raised with compost or fertilizer, respectively, in the nurseries.

The Problem of Soil Classification

The classification and mapping of soils depend mainly on subjective judgements. It is now generally agreed that the characteristics to be used must be based on the morphology of all the horizons in the soil profile. In English-speaking countries it is also agreed that the most convenient units are Soil Types or Soil Series, defined by features which have recently been fully described in the valuable new edition of the U.S.D.A. *Soil Survey Manual.* In areas which have been mapped for some time the names of the principal local Soil Types are as useful to specialists, farmers, and real estate agents as the names of plant varieties are to gardeners. Indeed, I have heard it argued that 'Miami Silt Loam' is as definite a term as 'Cox's Orange Pippin'. This is a weak analogy. The variety of apple is a single reproducible unit maintained vegetatively from a unique fusion of cells, whilst the Soil Type is only a conventional grouping of variable materials. The value of Soil Series or Soil Types as concepts lies in the demonstrable advantage of having soils studied and mapped by experts skilled in recognizing similar soils and relating their distribution and properties to other features of the landscape.

There are, however, many general questions for which it is necessary to combine these units into broader groups. Some writers, such as M. G. Cline (1949), have attempted to formulate basic principles for classifying all soils. A class is visualized by Cline 'as a group of individuals tied by bonds of varying strength to a central nucleus', defined by the modal value of some property, which is taken as a differentiating characteristic. Higher categories are to be sought by discovering other differentiating characteristics, which will group the classes into broader units without separating like things in a lower category. I think that Cline's system fails through starting with the concept of an individual soil as 'a thing complete in itself' and then following J. S. Mill's system of manifold classification. This logical system was developed for dealing with universal propositions in scientific proof and is quite unsuitable for the necessarily incomplete data used in scientific discovery.

Some early systems of classification which proved useful for treating animals or plants, salts, the simpler compounds of carbon and chemical elements are now known to have owed their success to determining

patterns of genes, ions, molecules, or electrons, respectively. In biology there were also evolutionary developments to be worked out.

Robert Boyle indicated the difficulty of defining and preparing pure substances with unique and reproducible properties. In an article entitled 'Concepts out of Context', N. W. Pirie (1952) has recently reminded us that the concept of 'purity' is not applicable to very large molecules, such as proteins, or that of 'species' to some of the smallest organisms and viruses. The nature and behaviour of these bodies depend, like those of soils, on complex and as yet ill-defined conditions in their environment.

Instead of attempting to treat a broad group of soils, e.g. 'podzols', as 'a complete natural body definable in terms of all its horizons and the relationships among them'—and independent of everything else—I think that we might profitably proceed in another way. We might pay more attention to the psychological and less to the logical factors in classifying natural phenomena. We could recognize that from an early age we develop the habit of individualizing, classifying, and naming recurrent impressions. With experience some specialists can develop high skills in extending these processes to events of great complexity. Scientific progress seems to depend less on devising formal schemes for classifying groups of events than on searching for quantitative relationships between them.

It is generally agreed that the principal factors in soil formation are related to climate, parent material, relief, living organisms, and time. Some workers have paraphrased this statement into a set of differential equations but, as the equations cannot be solved, this does not take us much farther. Early British workers stressed the importance of geology in soil classification because in Britain geographical and tectonic conditions combined to expose a wide variety of rocks, generally with the older ones in the cooler and wetter areas. Russian workers established the importance of studying the whole soil profile. The early workers studied the region between Moscow and the Caspian Sea, in which the seasonal pattern of rainfall is fairly uniform over a vast area of fluvio-glacial loess-like loams. From north to south the rainfall falls as the temperature rises, giving sharply contrasted climatic zones. Recognizing the zonal distribution of soil profile characters directed attention to the dominant influence of climate and vegetation in soil formation. The general climatic characteristics of the country were well known from experience or from school geography; there was no immediate need for quantitative studies. Data from a few cities sufficed to illustrate the argument.

In the United States soil survey followed a different course. It began by emphasizing the importance of texture in tobacco soils. The extreme contrasts between soils in humid and arid regions were brought out in Hilgard's important book, *Soils, Their Formation, Properties, Composition and Relations to Climate and Plant Growth in the Humid and Arid Regions*. Marbut, starting as a geologist, appreciated the work of the Russian school and adopted the profile basis of examination. He found many important classes of soil quite different from those described in

Russia. The zonal pattern was less clear in the United States because rainfall increased from west to east across the central and eastern States and not from south to north as in Russia. Marbut emphasized the natural soil under undisturbed vegetation. Kellogg extended the scope and practical value of the soil survey by emphasizing its agricultural aspects, and illustrated (1949) the modern viewpoint by describing soil as 'a dynamic three-dimensional piece of landscape, that supports plants'.

Great progress has been made in several countries in establishing geographical patterns and genetic relationships in the distribution of a number of soil series. Several recent writers in the United States (e.g. J. Thorp and G. D. Smith, 1949) are concerned about difficulties which may arise through confusing observed soil properties with inferred pedogenic factors in formulating a general scheme of classification. Many workers are anxious to give the greatest emphasis in soil classification to the profile characteristics of the soils themselves and to reduce as far as possible the geographic and genetic biases which tend to creep in.

I should like to offer the suggestions that we might give less attention to developing formal schemes of classification and that we might approach the problem from two complementary viewpoints; the first, by looking for convenient repeated units, such as Series, Families, Suites, Catenas, Great Soil Groups, bringing together similar or associated kinds of soils, even though these units may be based on quite dissimilar criteria and may overlap untidily; and the second, by searching for functional relationships between the distribution of these various soil classes and other features of the landscape, including historical ones.

The study of the functional relationships will require investigations on what for brevity may be termed 'internal' and 'external' aspects of the unit of landscape. This may require chemical studies on the distribution of salts, carbonates, and soil reaction (all of which may be measured in the field), and of organic matter, replaceable cations, sesquioxides, and clay minerals (all of which may require detailed laboratory work). The seasonal cycle in soil-water is one of the most important soil characteristics. Although the necessary information might be obtained from observations spread over all seasons, it is generally more reliable and certainly much more comfortable to infer most of it from meteorological data. Many of the external aspects of the landscape can be expressed quantitatively, whilst others must often remain in qualitative terms.

I am suggesting that we should seek to establish general relationships between various internal and external aspects of the unit of landscape. The method of correlation to be used will depend on whether the soil data to be examined are expressed as measurements on individual properties or in terms of areas mapped as having similar soils. Rigid statistical methods of analysis should be used wherever possible. Unless this is done we may repeat the mistake of the Russian soil geographer who, on seeing an American Prairie Soil for the first time in the tour following the First International Congress of Soil Science in 1927, contradicted a statement of the local rainfall on the grounds that it was

incompatible with the soil. A more serious mistake was made by Shantz and Marbut in their tentative map of the soils of Africa, when they put a chernozem belt across the savannahs to the south of the Sahara.

When some climatic correlations have been worked out more fully the soil surveyor and the ecologist may often be able to infer local climatic conditions with some confidence and thus prevent expensive blunders by enthusiastic agriculturists relying on scrappy local meteorological data. The climatic data used in the statistical analyses might include terms showing the seasonal distribution of rainfall and temperature. I think that mean monthly rainfalls and temperatures, both reduced to a few terms by harmonic analysis, will prove more serviceable than saturation deficits and other more elaborate meteorological data available from far fewer stations. I think, too, that conventional ratios and functions of independent values, such as Meyer's N.S. Quotient, should be avoided as prejudging the issues.

Correlations between soils and climates can be made on data grouped so as to allow for marked soil differences in geology, geomorphology, and history.

The search for general relationships might be regarded as an attempt to devise models in hyper-space to indicate the distribution of soils in relation to axes representing as many factors, both quantitative and qualitative, as can be observed and tested.

The problem of fitting soil classes to such a model is not as hopelessly complicated as might appear at first sight. Each of the units already found convenient in soil classification and mapping can be regarded as appropriate for certain selected projections of the model. Many of the old controversies and some recent arguments arose through trying to derive a unique and comprehensive system of classification for groups of material appropriate for different projections of the model. A single one of Bushnell's Catenas, which is defined as including 'all soil series which are homologous in characteristics due to climate, time, vegetation and parent material but which differ in characteristics due chiefly to varied drainage and land form', would be represented by a cluster of points in a projection on the plane representing the last two variables, and by a bundle of roughly parallel lines through the rest of the model. The various classes of Intrazonal Soils would cover many varieties of pattern through most of the model, but each of the separate classes would give a single cluster of points on a projection showing regional drainage and parent materials. The defect of the old concept of 'Intrazonal Soils', which has led many recent writers to reject this concept, was that it brought into a single category soils having little in common beyond their failure to conform with some other concept. An appropriate projection would reveal the characteristic features of the various groups of 'nonconformists' and, at the same time, the projection would direct attention to the 'Zonal Soils', which would more profitably repay detailed work on their climatic relationships. The model would also accommodate such observations as the occurrence of soils resembling chernozems in regions where both the parent material and the climate are markedly different from those in the area where this name first came

into common use among peasants. Indeed, the model would indicate that for a single class of soils any large variation in one environmental factor must be accompanied by a corresponding change in some other compensating factor. Systems of classification based on single differentiating characteristics are probably foredoomed to failure, except at the lowest levels of classification.

One great virtue of a hyper-space model is that parts of it can be used to illustrate the results of quantitative analyses of several correlated variables. It has been found in many fields of science, history, and politics that what Kellogg calls 'significant combinations of genetic factors' are difficult to recognize and interpret by purely observational methods.

As an additional step towards simplifying our task I think that there is a great deal to be said for recognizing the geographical limitations of much of our information. Thus, it has recently been stated (J. Thorp and G. D. Smith, 1949) that 'The Gray Wooded soils of Western Canada and the United States appear to be correlatives of the Gray Forest soils of Russia'. In the same way I think that we might refrain from treating chernozems as a single class and speak, instead, of American chernozems and Russian chernozems, until their relationships to one another and to their environments have been more clearly worked out. We know enough about the climates of the two areas to expect substantial differences between their soils. Admitting the geographical limitations of our current knowledge would amount to keeping together, for convenience, groups of soils following similar but as yet undetermined patterns in the model.

I should like to suggest that the interplay of ideas from looking at soil classification from the two alternative angles I have proposed might be more fruitful in generalizations of scientific value than striving for a single comprehensive system of classification. Those who have to draw small-scale maps may not agree with me, but, even in their work, it might be better to indicate by totally different systems of notation which parts of the map were based on the field observations of experienced surveyors and which were extrapolations inferred from miscellaneous data, such as geological maps, meteorological records, air-photographs, personal impressions, and travellers' tales.

The Art of Scientific Investigation

If, throughout my address, I may seem to have over-emphasized the search for repeating patterns and generalizations and given insufficient attention to deduction from established principles, I think that I could find support from many quarters, including recent developments in the philosophy of science, empirical philosophy, behaviourist psychology, and even brain physiology. Since our science is young, I might call on the testimony of many famous men of science about the early stages of other sciences, e.g. A. N. Whitehead's (1926) 'We cannot too carefully recognize that science started with the organisation of ordinary experiences. . . . It confined itself to investigating the connections regulating the succession of obvious occurrences', and C. Darwin's (F. Darwin,

1888) 'Science consists in grouping facts so that general laws or conclusions may be drawn from them'. For more recent statements and for a general discussion of research methods, I could refer to W. I. Beveridge's book *The Art of Scientific Investigation*.

I have tried to show how the kinds of experiment and observation we can make are determined by current theories and working hypotheses—how theory dictates method—and to emphasize the point that speculative thinking in many branches of science is influenced by ideas coming from both theory and practice. The more skilled, alert, and critical the worker the more likely he is to be able to profit by those unexpected experimental results or unusual observations which have so often pointed the way to new lines of progress by suggesting better hypotheses and the less likely he is to remain content with merely translating old ideas into modern technical jargon.

Perhaps I might try to illustrate the art of scientific investigation by a metaphor from agriculture. We know that our fields of work need to be fertilized with ideas from other sciences and from practice, but, first, we must clear away and keep under control the facile explanations and vague principles, apt to flourish as weeds on every kind of land. We must try to follow the advice of Hamlet:

> Do not spread the compost on the weeds
> To make them ranker.

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A CHRONOSEQUENCE OF SOILS AND VEGETATION NEAR MT. SHASTA, CALIFORNIA

I. DEFINITION OF THE ECOSYSTEM INVESTIGATED AND FEATURES OF THE PLANT SUCCESSION

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WITH FOUR PLATES

Introduction

SOIL scientists have long been interested in tracing the development of a soil from its initial undifferentiated state—the soil parent material. One of the earliest of such attempts was that of Dokuchaev (1883), who ascribed to the factor of age the differences in properties exhibited by soils on terraces of an elevation sequence along the Volga. More detailed investigations upon the rate of soil formation have subsequently been made by a number of workers (Tamm, 1920; Salisbury, 1925; Shaw, 1927; Hissink, 1938; Richardson, 1938; Aaltonen, 1939; Mattson and Lönnemark, 1939; Coile, 1940; Chandler, 1942; Ludi, 1945; &c.). Jenny (1941) focused attention upon the time factor in soil genesis when he attempted to summarize the generalizations emerging from much of this earlier work. He drew attention (1941, 1946) to the fact that in studying the development of soil properties as a function of time,

$$s = f(\text{time})_{\text{cl, o, p, r}},$$

consideration must be given to the 'constancy' of the climatic, biotic, parent-material, and topographic factors.

Few significant pedological generalizations have arisen from soil property–time studies, largely because of failure to establish the degree of significant variability in the environmental soil-forming factors in the systems studied. The authors believe that more reliable quantitative data relating to soil development are possible. If such data could be established for a sufficiently large number of combinations of climate, organisms, parent material, relief, &c., then not only might the more complex situations generally found in nature be better appraised, but, perhaps more important, a better basis would be available for investigating and understanding the soil-forming processes. We have deliberately sought out in our time studies, therefore, natural systems where we could establish a sequence of definite time states of a particular combination of climate, parent material, relief, and biota. The chronosequence near Mt. Shasta seemed to meet these 'rigid' requirements, and the series of papers initiated here deal with the changes of a number of properties of the soil body with time in this particular sequence, together with certain major and highly relevant developmental changes in the vegetation. A consideration of the interrelationships of the time states of vegetation and soil properties strongly supports the view already expressed by one of us (Crocker, 1952) that the ecosystem is a better

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theoretical unit than either the soil or vegetation systems, and, in addition, it emphasizes the great importance of organisms.

In analysing the ecosystem, or some segment of it such as the soil, in terms of a single-factor function, many theoretical problems arise in establishing conditions of uniformity of the other independent variables. The studies on the Shasta chronosequence not only illustrate the type of problems which arise but indicate some ways in which they can be resolved.

Location, General Characteristics, and Origin of the Chronosequence

The Shasta chronosequence is located on the conifer-forested south-east basal slopes of Mt. Shasta in northern California. It consists of a series of mudflow deposits, more or less superimposed in a regular stratigraphic sequence. The total area of the flows is about 8 square miles at an average elevation of 3,700 ft.

Many of the soils of California do not fall neatly into the accepted Great Soil Groups. Within any region, variability among the environmental soil-forming factors and their historic (in the broad sense) fluctuations, and differences in ages of surfaces, make the application of regional or zonal concepts especially difficult. The soils of the Shasta chronosequence show no apparent morphological differentiations with depth other than in the properties of colour, organic matter, and bulk density. However, the sequence occurs within a general region where many of the more common soils on older surfaces are tentatively recognized by the U.S. Division of Soil Survey as Grey Forest Soils. The Grey Forest Soils have some similarities with Brown Forest Soils, but are in general greyer, more acid, and show less of a textural profile.

The essential geologic features of Mt. Shasta have been described by Williams (1932, 1943). The formation of particular interest here is thick pyroclastic beds of tuff-breccia lying on the south-east slope of the mountain between 5,000 and 11,000 ft. elevation. They are exposed in the steep V-shaped walls of Mud Creek Canyon which has been cut 1,500 ft. into the side of the mountain. According to Williams the deposits represent detritus brought down as *volcanic mudflows*, possibly due to the rapid melting of ice and snow during volcanic eruptions. Mud Creek, issuing mainly from the snout of Konwakiton Glacier, has cut deeply into this material in comparatively recent times, removing roughly one-quarter cubic mile of debris in the process. A large part of this, possibly one-half of it, has been deposited below the mouth of the canyon and constitutes the source material of the modern mudflows of the present study.

Our investigations indicate that at least five mudflows of catastrophic dimensions, separated by substantial periods of years, have been associated with Mud Greek Canyon. The most recent flow occurred in 1924, and many accounts of it have been published (Williams, 1932; Beardsley and Cannon, 1930; Cooke, 1940; numerous Californian newspapers August–September 1924; &c.). It seems that this last flow might have resulted from a very unusual coincidence of certain climatic fluctuations and sequences with collapsibility of canyon walls and other factors.

According to observations of the 1924 mudflow, the material emerged from the canyon as a slow-moving mass having 'the consistency of concrete ready for pouring'. In this manner it buried the older soils in a virtually undisturbed state. The stream itself, with its numerous braided branchlets, appears to have ridden along with (and on top of) the mud. The continual blocking and overflowing of the stream and its subsidiaries left a complex pattern of now derelict stream channels and banks of stream-sorted material. Fortunately considerable areas were found apparently unaffected by stream sorting and subsequent erosion.

The pattern of deposition of the various mudflows must have been very similar, because they all evidence the same features, and in all cases the soils they buried show little disturbance. The particulate matter of all the mudflows varied enormously in size from huge boulders of volcanic rock to particles of colloidal dimensions. The vast bulk of it, however, consisted in each case of coarse sand, being essentially pulverized rock of andesitic composition, unmodified by previous soil-forming processes. To judge by the 1924 event, the mudflows had devastating effects upon the vegetation they overran. In the main, the new surface appeared as an area of barren packed sand with occasional projecting boulders or groups of boulders, having only a few dead tree-trunks protruding above it. Where the new deposit was thin, or on the banks of abandoned stream channels, a few well-established trees managed to survive.

The large 1924 mudflow buried part of the areas of two very much older flows, as well as most of two intermediate flows which had previously come down the same general route. It has been possible to establish in field investigations the stratigraphical relationships of all five of these flows. Their current surface exposures, labelled A, B, C, D, and E in order of increasing age, are shown in Fig. 1, prepared from aerial photographs and ground reconnaissance, while the stratigraphical relationships of the flows are indicated diagrammatically in Fig. 2.

The System studied

Before proceeding with the study of soil properties and some vegetation properties which develop as a function of time it is necessary to define the system subjected to analysis. Obviously, in the beginning the system consisted simply of a barren mass of rock material having no plant cover and no profile development whatever. With the passage of time the properties of this mass underwent many changes with the advent and progression of soil-forming processes. Plant and animal communities made their appearance and in a succession of infinitesimal changes, per unit time, proceeded from one particular assemblage of organisms to another. Concurrent with the biotic succession, a forest floor of organic debris in various states of decomposition developed.

Postulating that the soil-forming factors remain constant for a sufficient period of time, this *vegetation–fauna–forest floor–soil* system might ultimately reach a steady state of composition according to the theory of open systems (Bertalanffy, 1950).

For both theoretical and practical purposes this wider system, Tansley's

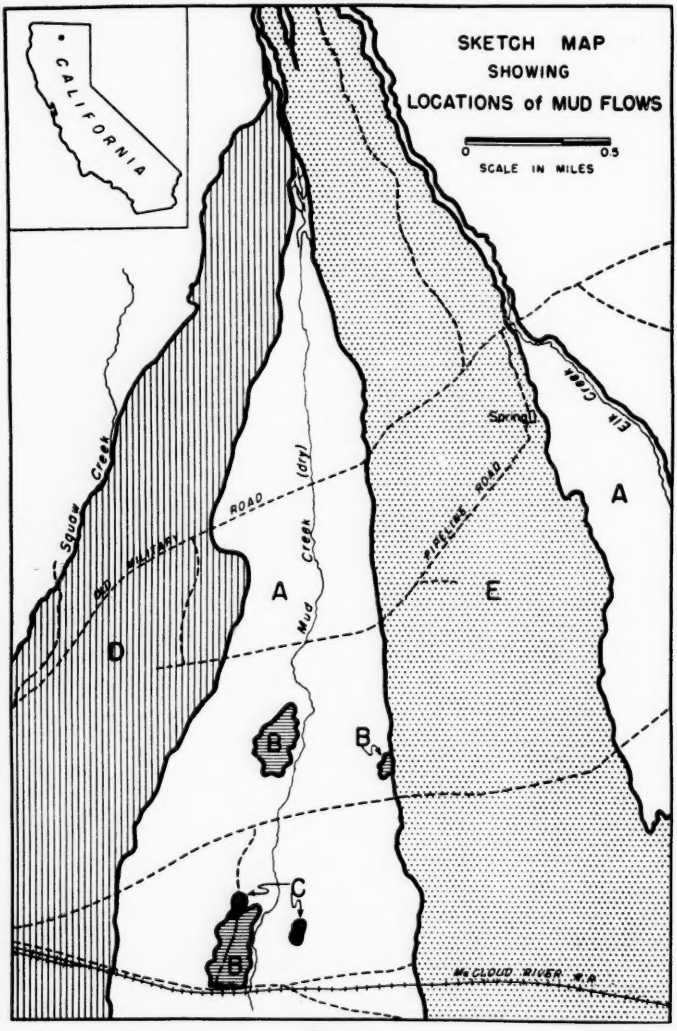

FIG. 1.

ecosystem, seems the best fundamental unit for study in nature (Crocker, 1952). However, for convenience and in order to simplify, it is both justifiable and necessary to subdivide this broad system, even though the divisions, such as that between soil and vegetation properties, have numerous arbitrary qualities. On our study the broader system was divided into a number of subsystems, some of which were studied fairly fully, and others of which were barely touched upon. These subsystems are set out in the following paragraphs.

Diagrammatic Section of the Mud Flow Area
Showing Stratigraphic Relationships, Buried Soils,
and the Vegetation

Mud Flow Ages		
A	27	years
B	60	"
C	205	"
D	566	"
E	1200+	"

FIG. 2.

Subsystem 1. The vegetation. Many ecological aspects of the plants, density, cover, layering, composition, &c., are dependent properties of the system which can be conveniently recognized for separate study.

Subsystem 2. The forest floor. The forest floor, consisting of plant and animal residues and their more or less decomposed counterparts, constitute another observable and relatively discrete segment of the system.

Subsystem 3. The fauna. No investigations of this subsystem were made. However, animal populations, deer and squirrels especially, were noted to be very much greater on the older soils, that is, were dependent upon the time-state of the systems.

Subsystem 4. The 'mineral' soil. This was considered to be that portion of the system extending in depth into the mudflow mass from a point just under the forest floor to a point where the effects of the soil-forming processes were apparently no longer significant.

Subsystem 5. Pinus-ponderosa soil. In as much as soil profile and forest floor samples in our investigations were limited to sites under *Pinus ponderosa*, the *Pinus-ponderosa* soil substrate was singled out for special attention.

The Factors determining the Ecosystem

In expressing the properties of the mudflow soils or vegetation in terms of variation with time, the constancy of the independent determining factors must first be established. This presents numerous problems to be discussed more fully in a later paper. In the following paragraphs brief assessments of the determining environmental factors are presented together with an evaluation of the time factor. These readily establish a high degree of uniformity.

The time factor

The chronological order of the five deposits was clearly determined by the stratigraphic evidence. The ages of the four youngest members of the sequence were determined by the age of the oldest trees found growing upon the actual surface of each deposit, and which were not growing on any buried soil below. The observations of Beardsley and Cannon (1930) showed that pine-trees became established within 1 or 2 years after deposition. The oldest trees, therefore, can be accepted as valid criteria of age. The values for the time factor thus determined were 27, 60, 205, and 566 years for flows A, B, C, and D respectively.

The age of the oldest surface greatly exceeded the life span of the trees growing upon it. However, a conservative estimate of its age was made on the basis of the morphological characteristics of the soil formed upon it which was buried 566 years ago by flow D. This buried soil was obviously in a formation state *at least* equal to the 566-year soil itself. It was concluded, therefore, that flow E must be at least twice as old as flow D. For this reason the age of flow E will be designated as 1,200+ years throughout this study.

The climate factor

Climatic data have been recorded at McCloud, about 2½ miles from the centre of the flow area, for the past 40 years, and are summarized in

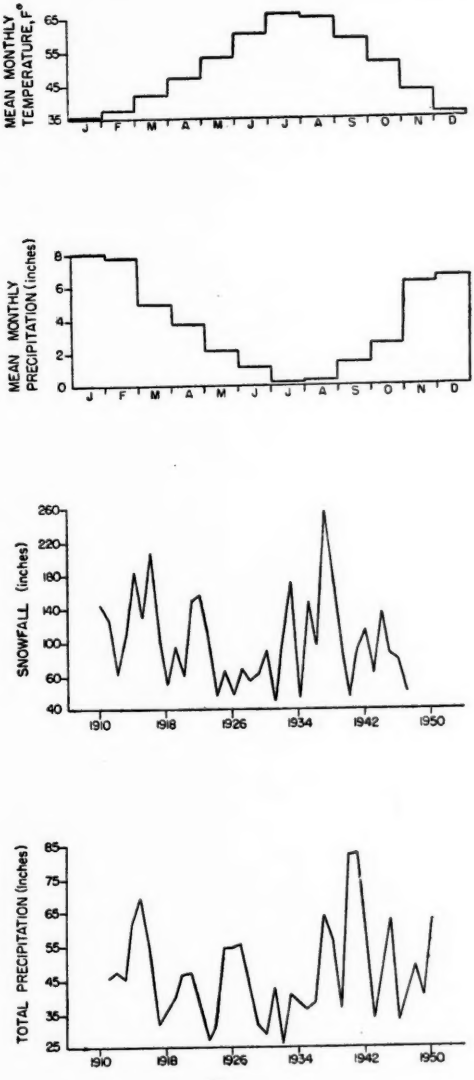

FIG. 3.

Fig. 3. These data are taken from the appropriate reports of the United States Weather Bureau.

The average annual precipitation is 46·6 in., of which 35 in. occur in the 5 months November through March. Exceptionally wet months of

20 to 23 in. have occurred occasionally. The average for July and August, the driest months, are 0·20 and 0·21 in., but very frequently these months have been rainless.

Normally snow begins to fall in November and ceases in April. The average snowfall is 102 in., but has been as high as 258 in. (1937) and as low as 34 in. (1934).

The average annual temperature is 49·6° F., varying from 35·1 in January to 65·9 in July. The average daily maximum and minimum are 65·0° F. and 33·3° F. respectively. The average dates of the last and first killing frosts are 11 June and 13 September (94 days frost free). No records of evaporation are available.

In general, the present climate is a wet-dry temperate climate suitable for the luxurious growth of coniferous forest. All five flows obviously have currently identical regional climates.

The parent-material factor

The parent material in all five flows was a mass of pulverized rock of hornblende-andesite composition. The degree of chemical uniformity of the parent material and the relatively simple mineral assemblage is demonstrated by the following mineralogical analysis (Table 1) of the fine sand fraction (0·25–0·1 mm.). The first four members can be regarded as mineralogically uniform. The oldest member has less amphibole and more pyroxene, although the whole heavy fraction was not significantly different.

The physical variations of particle size, internal stratification, stream sorting, erosion depth, and apparent density were largely reduced to negligible importance by the selection of sampling sites. The sites chosen were for material of coarse-sand texture with a variable stone content. The stones were generally less than 2 in. in diameter. The mean apparent density was 1·63 g./c.c. (range $\pm$0·13) in the 'C' horizon material. The data on particle-size analysis of the 24–36-in. horizons (Table 2) further attests the physical uniformity of the five mudflows.

While the parent materials are not absolutely uniform, it is doubtful whether greater uniformity could ever be expected for natural systems.

Within the parent-material factor we are including those independent determining factors which relate to position of the site relative to neighbouring ecosystems. These include, for example, site location relative to seed source. It might be better to consider these aspects as a separate factor, but it is more convenient for the time being to include them under parent material.

The topographic factor

All the mudflows have the same general slope, relief, exposure, and elevation. Here again any variations which existed were resolved in our study simply by the selection of comparable sampling sites. The general slope was about 4·7 per cent. on a south-east exposure. All samples were taken within the elevations of 3,450 and 3,850 ft. on areas of smooth relief.

TABLE 1

Mineralogy of the Fine Sand Fractions of the Parent Materials

	Mineral fraction	*Age (in years)*				
		27	*60*	*205*	*566*	*1,200+*
% by weight	Heavy	17·6	18·4	18·8	18·6	19·2
	Light	82·4	81·6	81·2	81·4	80·8
	Heavy Magnetite	1·8	1·8	1·6	1·8	1·7
% by grain numbers	Heavy*					
	Hypersthene	65·3	63·8	68·3	67·0	79·4
	Augite	3·0	2·5	3·3	3·3	4·3
	Hornblende	21·3	23·5	15·7	20·0	8·3
	Basaltic hornblende	10·3	10·3	12·7	9·7	8·3
	Light					
	Plagioclase	40·0	41·9	39·8	38·7	30·3
	Volcanic glass	7·3	5·7	5·1	4·7	4·0
	Volcanic rock	52·6	52·4	55·1	56·7	65·7

* Magnetite-free heavy fraction.

TABLE 2

Particle-Size Analysis of the Parent Material

Age of flow	*Particle size, % by weight organic-matter-free gravel-free soil*								
	2 mm.	*0·5 mm.*	*0·25 mm.*	*0·1 mm.*	*50 μ*	*30 μ*	*3·8 μ*	*1·5 μ*	*Gravel > 20 mm.*
27	37·1	13·1	19·2	12·3	5·7	8·4	2·1	2·1	37
60	25·0	15·3	24·5	14·8	6·8	8·8	3·1	1·7	6
205	26·1	16·0	26·1	14·2	4·9	9·0	1·8	1·9	11
566	29·5	16·2	25·7	13·7	1·8	7·6	1·8	3·7	40
1,200+	27·8	16·8	25·3	14·2	3·5	8·4	2·3	1·7	45

At least one spring comes to the surface in flow E, near Elk Creek. However, the effect of this spring is extremely local; elsewhere the porous masses of coarse sand are well drained and dry out to considerable depths in the summer months.

The biotic factor

The definition of the biotic factor employed by the authors was that recently set forth by Crocker (1952), and differs from both Jenny's (1941) concept and Major's (1951) definition in recognizing that biotypes differ in their effectiveness as soil-forming agents. It is not possible at present to make any reliable assessment of this effectiveness or qualitative aspect of vegetation, except upon rather crude grounds. But, on the basis of the duration of prominence in time, and proximate areal volumes occupied by plant species, the flora of the flows can be broadly and tentatively

grouped as effective, moderately effective, and non-effective. Omitting very inconspicuous species these groups were—

Effective: *Pinus ponderosa*,[1] *Pinus lambertiana*, *Pseudotsuga taxifolia*, *Libocedrus decurrens*, *Quercus kelloggi*.

Moderately effective: *Ceanothus velutinus*, *C. cordulatus*, *C. prostratus*, *Purshia tridentata*, *Arctostaphylos patula*.

Little or non-effective: *Abies concolor*, *Acer glabrum*, *Alnus viridis*, *Ribes roezlii*, *Prunus emarginata*, *Salix* spp., *Populus trichocarpa*, *Cornus californica*, *Leptodactylon pungens*, *Symphoricarpos* sp., *Stipa occidentalis*, *Festuca megalura*, *Bromus tectorum*, *Pteridium aquilinum*.

The definition chosen for the biotic factor is governed somewhat, for practical reasons, by the type of system which is being investigated. Up to a point one can make this very narrow. For example, in the soils aspect of this study the need for an effectiveness classification of the plant factor was largely avoided by restricting the system to beneath the branch periphery of first-generation *Pinus ponderosa*. This introduces the assumption that *Pinus ponderosa*, as well as the forest floor and soils under these pines, was uninfluenced by neighbouring vegetation. This assumption cannot be rigorously justified, especially for the two older systems. However, as a first approach, it seems far less open to objection than any of the alternatives.

The effective faunal aspects of the biotic factor include deer, squirrels, chipmunks, gophers, and moles (Merriam, 1899). Their possibilities for occupation of the ecosystems under investigation were essentially dependent, immediately at the initiation of any particular system, upon neighbouring ecosystems and their time states, and entirely independent of the new system. Because the areas of the mudflow are relatively small and the fauna so mobile, it is therefore quite reasonable to consider the independent faunal aspects of the biotic factor as 'constant' for all systems.

General Assumptions

The general uniformity, for the five systems investigated, of the climatic, biotic, topographic, and parent-material factors indicated above leaves a residue of more difficultly established constancy aspects for more rigorous treatment. These aspects can only be resolved by making assumptions. The reasonableness of these assumptions largely determines the value and acceptability of any time functions. The main assumptions made are:

1. The present average climate has existed throughout the full period, at least to the extent that any climatic fluctuations have been pedogenetically insignificant.
2. The biotic factor is completely represented, as given, and each system has had the same succession of biotic assemblages in so far as its age has permitted.

[1] Botanical nomenclature from Jepson's *Manual of the Flowering Plants of California*. Assistance with identification by Botany Department, University of California, is acknowledged.

3. The small variations in the states of the systems at zero time (parent materials) were insignificant, and no pedogenetically significant substances have been added differentially (e.g. volcanic ash) since zero time.
4. The hydrologic régimes at zero time were the same in all systems, and no basic changes in hydrology, other than those introduced by development of the ecosystem, have occurred since the deposition of the individual flows.

A priori these assumptions can never be completely examined. However, in this study the existence of apparently undisturbed buried soils, and the shortness of the period, afforded a greater opportunity for drawing conclusions about the past than is usually possible. On the basis of the general field evidence the authors' initial judgement was that the above assumptions were at least as valid as those of previously reported investigations. We proceeded on this premiss, and believe that this judgement was vindicated by further analysis. The refinement of the conclusions to be made from our data will depend upon the degree of vindication one allows for the final analyses of these assumptions. This analysis is made in a later paper of this series. For the time being the assumptions can be accepted as quite reasonable.

The Vegetation and Vegetation Dynamics

While no full ecological analysis has been attempted, a limited number of generally acceptable vegetation properties have been assessed in order to characterize the vegetation and its dynamics, and especially to serve as a basis for evaluation of its significance in relation to the development of soil properties.

Methods

On the basis of general observation, a typical area for each member of the sequence was selected for detailed examination of the vegetation. Data was collected by means of thirty 20-ft. square plots laid out in a belt transect. The individuals of each species were then counted directly and, on the basis of the layers in which they occurred, segregated into three categories. These layers were: (*a*) tree layer (dominant trees, mainly near-original conifer inhabitants); (*b*) sub-tree layer (oak and young conifers); and (*c*) shrub and ground vegetation layer.

Percentage ground cover for each species and *basal area* for the dominant pine-trees were estimated, and *frequency* of occurrence per hundred plots calculated for each species. Because the oldest forest cannot be regarded as first-generation forest and has suffered from fire shortly after logging at the turn of the century, its value in succession studies is very limited. Data relative to it should therefore be accepted with reserve.

The total sample plot area for each member of the sequence was 12,000 sq. ft. For purposes of illustrating the broad features numbers of species and basal areas are reported on this area as a unit.

General description of plant communities

Flow A. The vegetation on the 27-year-old mudflow was a sparse community dominated by *Pinus ponderosa* and *Purshia tridentata* with about 70 per cent. bare ground (Plate I). Other species were present but much less noticeable. Fifteen per cent. of the cedars counted were dead or dying. At the outer edges, near the more important seed source, a relatively narrow and dense belt of young pines with much less *Purshia* usually occurred. This graded to another extreme near the centre of the broader parts of the flow, where trees were exceedingly sparse and the scene was dominated by *Purshia* or even large areas of bare ground. Stone and boulder content in some local areas were so great as to influence botanic composition.

As stratification was indistinct at this age, an arbitrary division was made to include the larger of the intermediate trees in the tree layer and the remainder with the shrubs.

Flow B. The striking characteristic of the 60-year-old vegetation was its uniformity. It was a comparatively dense stand of *Pinus ponderosa* having no understory. Remains of dead shrubs were seen in some places, but there was no evidence of their regeneration.

Although most of the trees were near-original inhabitants, about 30 per cent. of them were younger. These were tall and thin, and almost all of them were either dead or dying. They were recorded in the sub-tree layer. Firs and cedars although present were rare, while oaks although more abundant were nearly all seedlings less than 20 in. high. The general appearance of this forest is shown in Plate II.

Flow C. The 205-year-old forest was characterized by an open aspect (Plate III) with a comparatively good cover of grasses, a re-encroachment of shrubs, and a somewhat greater prominence of oaks and cedars. Stratification in our broad terms was quite clear, the near-original conifers towering far over the oaks and younger trees. Occasionally firs and cedars occurred, although they were not present in the sample plots. All of the tree species were found in the sub-tree stratum, however. In the shrub layer *Prunus emarginata* and *Ceanothus cordulatus* were present, but *Arctostaphylos* and *Ceanothus velutinus* were absent or rare. Bracken made its first and only notable appearance in the sequence.

Flow D. The 566-year-old forest (Plate IV) was vastly different from its 205-year-old predecessor. The most striking feature was the prominence of the firs. A great many of these had ages less than 350 years, strongly suggesting that they had begun their invasion shortly after the 205-year mark. The forest was no longer 'open', the spaces having been taken by firs and cedars and by the appearance of a substantial sub-tree stratum. The shrub layer, although different in character, was not appreciably different in volume from that of the 205-year forest. The oaks had continued to increase, but not in the spectacular manner of the firs.

The forest on the two oldest flows (D and E) had been logged about 1885. Only the very best trees were apparently taken. It was not difficult therefore to choose little-affected areas for the soil samples, but the vegetation sample plots undoubtedly reflect the logging influence.

Thus the changes in the shrub species and their frequencies and the great increase in tree seedlings can be partly ascribed to these activities.

In general the 566-year forest can be described as having all the features of a mature first generation forest.

Flow E. The character of the forest on the oldest flow is difficult to assess because here logging activities were more intense, and soon afterwards the extensive fire occurred. However, from consideration of the density and kinds of stumps left by logging in areas where they were little affected by fire, it seems likely that the pre-logging forest was little different from the current forest on the 566-year flow. Pine density appears to have been about the same, while cedars were probably more frequent and firs correspondingly less so than in the 566-year forest.

The vegetation as a function of time

The broad features of a primary plant succession are reflected in the vegetation of the sequence of flows. The succession trends in the vegetation, allowing our earlier assumptions, are symbolized by Major's (1951) modification of Jenny's equation, namely

$$\text{vegetation} = f\,(\text{time})_{\text{cl, o, p, r...}}$$

Such properties of the vegetation for which we collected quantitative data are now briefly presented.

Frequency

The frequency (the ratio of the number of plots in which a given species occurs to the total number of plots, expressed as a percentage) gives an indication of the variability in space distribution of the main species. In Table 3 frequency values obtained from the belt transect plots are summarized.

In general, the frequencies of all species except pine and oak suffered a sharp decline in the 27–60-year period. The oak figures are misleading in that the majority of these individuals were inconspicuous seedlings.

The occurrence of maximal frequencies of bracken and grasses in the 205-year forest seemed to be characteristic of the sequence. With the 'opening up' of the forest after considerable soil formation had taken place, it was considered reasonable that this should occur. When the forest was 'closed in' later by the ascendancy of firs, cedars, and oaks, the environment probably became increasingly unsatisfactory for bracken and grass.

Abundance of trees and shrubs

Data for abundance of species for the tree layer, sub-tree layer, and shrub and seedling layer were obtained. The complete data is available (Dickson, 1952), but only that relative to the trees is presented here. While special efforts were made to avoid misleading logging influences in the two oldest forests, the possibilities of such influences must be borne in mind.

TABLE 3

Frequence of Occurrence of Species

	A 27 years	*B* 60 years	*C* 205 years	*D* 566 years	*E* 1,200+ years
*Pinus ponderosa**	84	94	67	67	61
Libocedrus decurrens	77	23	57	90	100
Pseudotsuga taxifolia	30	4	7	97	73
Quercus kelloggi	20	67	64	77	84
Purshia tridentata	100	0	20	0	48
Arctostaphylos patula	17	0	0	13	28
Ceanothus spp.					
C. velutinus	0	0	0	20	44
C. cordulatus	0	0	17	20	0
C. prostratus	4	0	0	37	12
Prunus emarginata	23	0	17	7	0
Ribes roezlii	0	13	0	0	0
Pteridium aquilinum	0	0	20	0	0
Grasses	33	4	100	27	7

* Includes also occasional *P. lambertiana*.

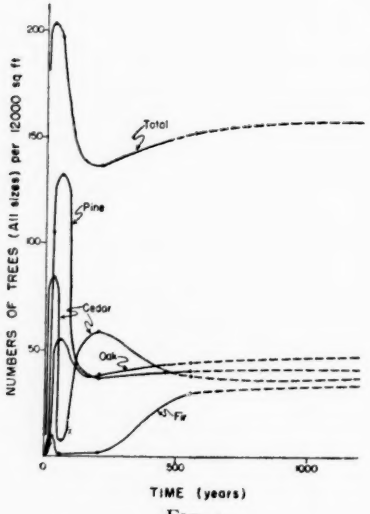

FIG. 4.

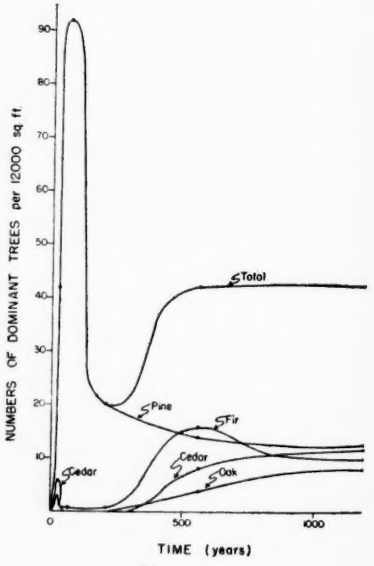

FIG. 5.

In Fig. 4 the number of trees per 12,000 sq. ft. are plotted relative to age of the flow surfaces. Fig. 5 presents similar time functions for dominant trees only, and gives a clearer picture of the general appearance of the forest. This figure illustrates the thinning of the forest in the 60–205-year period, followed by the increase in prominence of fir and cedar.

Percentage ground cover

The percentage cover results, plotted as curves against time, in Fig. 6, are based upon estimates and are therefore somewhat arbitrary. However, the authors have confidence in their main features, and believe they illustrate quite clearly the changes in the general character of the forest.

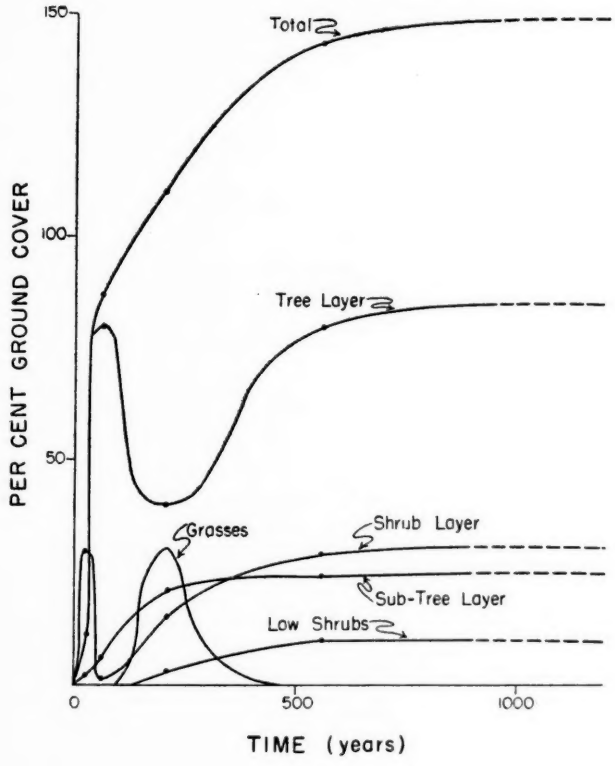

FIG. 6.

It is interesting that the total percentage cover, as here estimated, increases by diminishing increments and asymptotically approaches an apparent steady state value of about 150 per cent.

The dominant pines

Special attention is directed to the dominant pines in the soil property investigation, and the ecological data relative to them (*Pinus ponderosa* plus *P. lambertiana*) are plotted in Fig. 7.

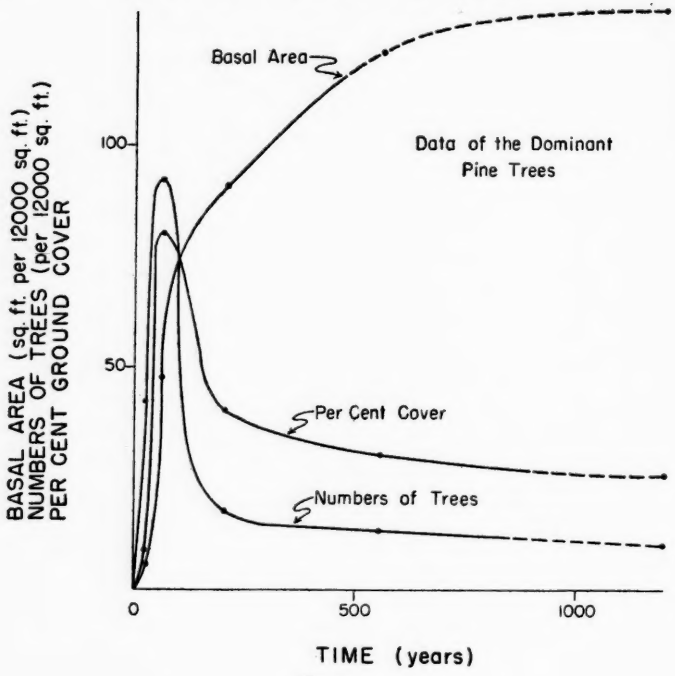

FIG. 7.

Significance of the ecological data

The ecological data, although focused upon the prominent species, is quite adequate for our purposes. Explanations which provide reasonable connecting trends between the observed forests can be made. Such interpretations, together with some theoretical problems associated with them, are developed in the following discussion. Other interpretations are no doubt possible, but those proposed seemed most satisfactory.

The spatially dispersed character of the 27-year forest strongly indicated that development in this period was essentially a question of placement, lodgement, and frequency of viable disseminules capable of establishment on the barren sands of the mudflow. Unquestionably the parent-material factor, the physical state of the mudflow at zero time (including its distance from the seed source), was the principal determinant of the vegetation in the initial stages. It was evident that all of the potentially effective germules (biotic factor) arriving on the mudflow did not have equal establishment ability in this early stage.

Comparison of the 27-year and 60-year forests indicate that for the former to develop to the latter, the abundance of pines must increase from 84 to 133. This means 49 new seedlings must become established. It is only necessary to allow that 8 of the new seedlings shall become 60-year dominants to arrive at the identical abundance observed in the

60-year forest. This is therefore quite a reasonable prediction. Since very few pines less than 20 years old occur in the 60-year forest, most of the 49 new seedlings must become established within the next 10 or 15 years. This could readily be achieved with the average establishment rate demonstrated for the 27-year forest.

The thick forest floor in the 60-year forest, for which evidence of very recent (preceding 5–10 years) build-up exists, together with the closing canopy of touching tree-tops, is adequate to explain increasing inhospitableness towards new individuals.

The development of the 205-year forest from one like the foregoing requires that a thinning of the pines shall occur. The observation of a vigour series, ranging from death to maximum vigour, was readily observable within the 60-year forest. Thirty per cent. of them were already dead or apparently so. This was essentially a 'competition' effect. It could be predicted quite reasonably that the required number of trees slated for extinction (56) to correspond to observed differences between the two forests might be attributed to these causes. Evidence for this process exists in the age-class distribution of trees in the 205-year forest. Here there was a large number of trees older than 140 years, and another large group less than 60 years of age, but few of intermediate age. This absent intermediate group probably represents the eliminated trees.

Comparison of the 566-year forest with the 205-year forest characterizes the 360-year interim period as essentially that of a 'filling-in' process. Although the abundance of pines did not change, their appearance did, for example, basal area, total height, &c., and so also did the effective ecological conditions for the lower strata. It seems that these subtle changes within the forest had some selective value operating in favour of the firs, despite the fact that cedars probably became established first. The elimination of many of the young cedars present at the beginning of the period was probably due to the fact that their pattern of distribution was that of rather dense clumps as evidenced by their relatively low frequencies (57 per cent.) in the sample plots. Nevertheless both cedars and oaks gained a significant place in the forest during this period. Support for this predicted development of the 205-year forest is provided by the age classes of firs in the 566-year-old forest, where most of the firs were less than 350 years old.

The general developmental trends outlined above can certainly be accepted as the broad features of a primary vegetation succession. Tansley (1926, 1935) has suggested that all successions can be regarded as *allogenic* or *autogenic*, depending upon whether the dominating factors of change are external to the actual plants (allogenic factors) or directly due to the activities of the plants (autogenic factors). While recognizing that both allogenic and autogenic factors might both operate, he has also implied that primary successions (priseres) are essentially autogenic. There seems little theoretical or actual support for this view. *Autogenic* and *allogenic* are useful terms, but primary plants successions do not fall neatly into one category or another. In our system the dominating factors in the early stages of the succession are allogenic, the significant

thing being the pattern of viable disseminules. Any of the ultimate dominants might become established from the start. However, in so far as the ecological significance of fir and cedar changes as a result of the influence of the preceding vegetation the factors are autogenic. A better approach is to look upon developmental change in vegetation towards a relatively steady-state condition as merely representative of the time state of the ecosystem.

Summary

The chronological order of five mudflow deposits of coarse andesitic sand has been established by stratigraphic evidence. The ages of four of them were determined by means of tree ages as 27, 60, 205, and 566 years. An estimate of 1,200+ years for the oldest deposit was made on the basis of the morphological properties of its buried counterparts under deposits of known ages.

Ecological evidence showed that each forest was a logical successor to previous stages on the projected time scale and that the forest reached an apparent steady state within the 1,200+-year period. The initial stage was characterized by a random distribution of effective germules capable of establishment on barren sands. The subsequent growth of the pine-trees resulted in an overcrowded condition resulting, firstly, in a suppression of nearly all other species; secondly, a heavy leaf drop from the pines; and thirdly, an elimination of younger and weaker pine-trees. The further growth of the surviving pines resulted in an 'open' aspect, encouraging the re-encroachment of other species: firstly, grass, bracken, and shrubs; secondly, oak- and fir-trees; and ultimately, cedar-trees.

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A CHRONOSEQUENCE OF SOILS AND VEGETATION NEAR MT. SHASTA, CALIFORNIA

II. THE DEVELOPMENT OF THE FOREST FLOORS AND THE CARBON AND NITROGEN PROFILES OF THE SOILS

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Introduction

In the initial paper of this series the location and general character of a sequence of five soil-vegetation systems, differing mainly in their ages, were described. The systems were defined and the developmental changes in vegetation properties as a function of time were outlined. In the present paper the time states of the properties most closely related to the vegetation, namely those of the forest floor, and the carbon and nitrogen profiles are considered.

Although much work has been done on the morphology, decomposition rates, and composition of forest floor materials, the development of this natural body as a function of time has received but scant attention, while many workers have completely neglected it altogether. Lutz and Chandler (1946) emphasize the need for such studies.

The authors believe that, due to the unique circumstances offered by the Shasta chronosequence, the rate of development of the total organic profile, the differentiation of the organic phase into layers, and the relationship of these changes to the developmental characteristics of the vegetation, are more subject to precise investigation than has been possible heretofore.

General Characteristics of the Forest Floors

We have used the term *forest floor* in the sense adopted by the Third International Congress of Soil Science, namely, the layer of organic debris and its more or less decomposed counterparts, which rests upon, and is reasonably distinct from, the mineral soils below. We regard it merely as a less permanent segment of the much larger system in which the forest, forest floor, and soil develop simultaneously with the progress of time. At the initiation of our systems there was no forest floor. It began to accumulate with the establishment of vegetation.

On the 27-year mudflow the forest floor was practically limited to the ground space immediately beneath each individual plant, and the floor under a particular species represented almost absolutely the litter of that species. Relative to age of tree the pines had produced the heaviest litter. Under 26-year-old *Pinus ponderosa*, for example, a maximum depth of about $\frac{1}{2}$ in. of litter had accumulated. It showed no differentiation into horizons.

The 60-year-old forest floor was a more or less uniform deposit of pine residues (75 per cent. needles and 25 per cent. small twigs) some $3\frac{1}{2}$ in.

deep, the contribution of other species being almost negligible. This floor was much more uniform, both in depth and character, than that on any of the other sequences. In contrast to the simple layer of raw pine litter on the 27-year flow, it exhibited considerable morphological differentiation. A surface layer of comparatively fresh pine-needles 1¾ in. thick overlay a weakly matted, somewhat crumbly, fungal-infested layer of equivalent thickness, where the needles were considerably broken down. This underlying layer was regarded as the fermentation layer. The demarcation of these zones was comparatively sharp. Considered against the fermentation layers of the three older systems, this floor appeared to be in a state of maximum decomposition activity.

The 205-year-old forest floor again exhibited considerable variability in parallel with the characteristics of the forest already described. Along a transect from a more open grassy patch towards the base of a pine the floor thickness increased from almost zero to a maximum thickness of about 4½ in. some 4 or 5 ft. from the trunk. At the point of maximum thickness under the pines the fermentation layer was about 3 in. thick, or about twice as thick as the overlying litter. The differentiation of the zones, however, was not as distinct as in the 60-year-old forest floor, nor was fungal activity as apparent. Locally the floor had been disturbed by moles and other animals which had not been factors in the two younger floors.

While variable in character from place to place, the floor of the 566-year-old forest was not nearly so variable as the 205-year floor. However, at any site it reflected the neighbouring dominant tree composition. The floor under a fir, for example, was qualitatively different than under a pine. Under the larger pines the floor was about 2½ in. thick, the upper inch of which was raw litter.

The forest floor on the oldest surface was little different from that of the 566-year member except for the greater prominence of cedar litter.

The Composition of the Forest Floors

Methods

The forest floor samples which were selected for analyses were taken uniformly from the zones of maximum accumulation under *Pinus ponderosa*. The samples bear no relationship to areal extent or forest floor variability over the mudflows as a whole. This variability was purposely avoided in the confinement of our quantitative analysis to a particular part of the *Pinus ponderosa* floor, and this species was chosen largely because it flourished dominantly on all five mudflows. Other sites might have been selected to give different values that may have resulted in somewhat different conclusions.

The samples were taken by means of a knife-edge sampling tool of one square foot dimensions. The mineral soil profile samples were taken directly below the forest floor samples. The boundary of the forest floor and mineral soil was sharp in all cases, but that between the litter (L) layer and fermentation (F) layer was more arbitrary. No recognizable humic (H) layer was present.

Botanical composition of the L layer

The identity of most of the botanical components was readily recognizable in the litter (L) layer. These were hand-separated and recorded as per cent. by weight. The data, which are plotted in Fig. 1, although taken directly under the pine, reflect to a limited extent general ecological characteristics of the forest.

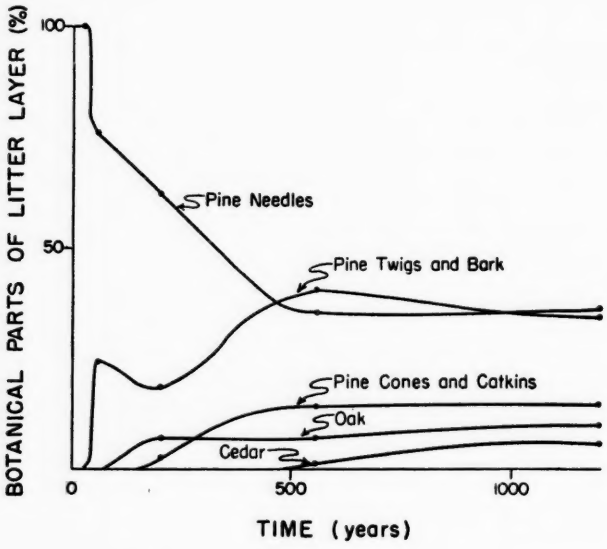

FIG. 1.

Other properties of the forest floors

The floor samples were ground in a Wiley mill to pass a 60-mesh sieve and determinations of pH, volatile matter, sand and silica,[1] carbon,[2] nitrogen,[2] and water were made. These are plotted as a function of age in Fig. 2 and are recorded also in Table 1.

The total weight of the forest floor per unit area at the points sampled increased sharply to a maximum at the 205-year point, but was approximately only half that in the older forest.

The amount of sand and silica (chiefly admixed sand, silt, and clay particles) was both considerable and variable, yet the quantity of volatile matter per unit area, the amount of carbon, and total nitrogen per unit area all showed time functions of very similar shape to those of total weight.

The carbon-nitrogen ratios dropped rapidly from a value of 107 in the youngest member to values of 60, 47, 57, and 50 in the four oldest

[1] Association of Official Agric. Chems., 1940.
[2] Walkley and Black, 1934.

TABLE I

Composition of the Forest Floors

Time	*Layer*	*Weight (g./0·05 sq. ft.)*	*pH*	*Water %*	*Carbon %*	*Nitrogen %*	*Volatile %*	*Sand and silica %*	*Si-free ash %*
27	L	7·1	4·19	4·38	58·8	0·550	84·7	13·0	2·23
60	L	24·1	4·22	6·64	58·8	0·772	94·6	3·8	1·63
205	L	24·2	4·51	5·08	59·3	0·947	95·4	2·5	2·18
566	L	14·5	4·38	6·16	58·8	0·701	95·7	1·9	2·34
1,200+	L	9·6	4·38	4·63	59·3	0·842	95·0	2·7	2·34
60	F	27·3	4·63	8·12	35·2	0·772	58·3	38·9	2·77
205	F	51·0	4·97	8·67	49·2	1·195	78·4	18·4	3·22
566	F	21·7	4·70	7·59	49·2	1·075	82·6	14·1	3·31
1,200+	F	30·3	5·16	4·24	39·3	0·890	65·2	29·7	5·08

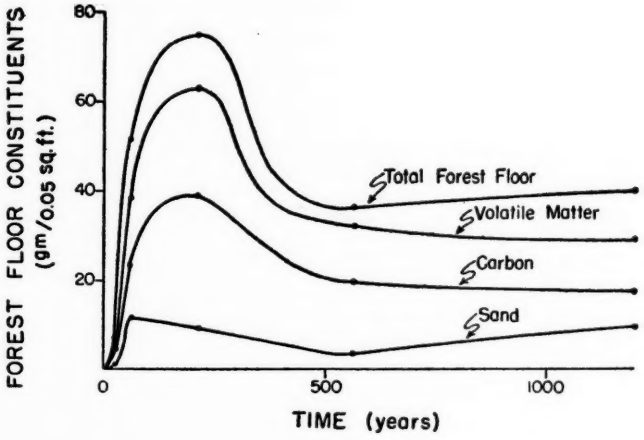

FIG. 2.

members. The drop in C/N value, however, was more precipitous in the F-layer than the L-layer (Fig. 3).

The pH of all of the forest floor samples were between the limits of 4·2 and 5·2 and were more acid than the soils underneath. The principal observation was that the pH of the L-layer remained about the same, whereas the F-layer was significantly less acid from the time of its first appearance in the sequence (Fig. 4). This seems to be in accord with published results (Lutz and Chandler, 1946). The similarity between the pH functions and the silica-free ash functions (total ash less sand and silica) suggested that there was a close connexion between these measurements.

Comparisons of many of the results for the F and L layers indicate the rate at which many substances accumulate (concentrate) in the F layer.

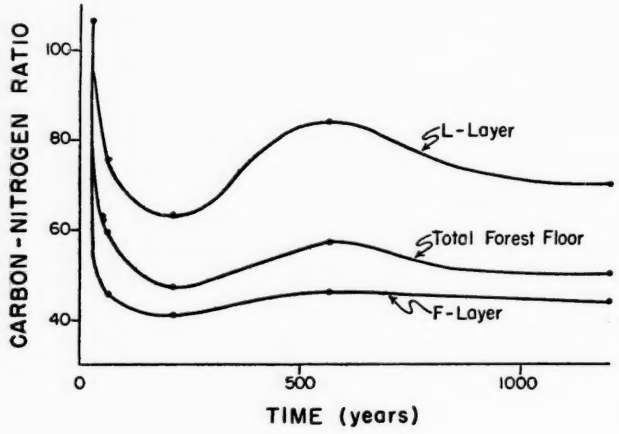

FIG. 3.

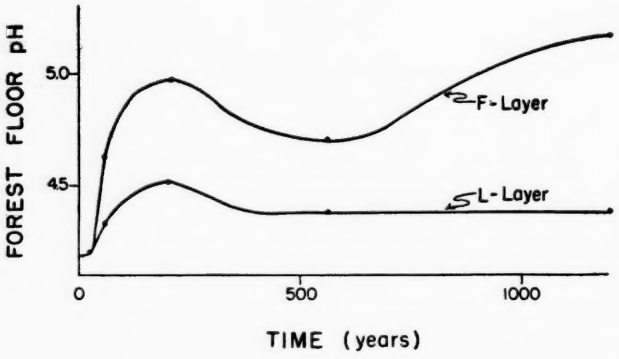

FIG. 4.

Organic Carbon and Nitrogen of the Mineral Soil Profiles

The soil samples

The soil profile samples were taken directly beneath the sites chosen for the forest floor samples. The term soil, as previously defined, is used to mean that part of the system which lies below the forest floor. Five samples were taken from each profile 0–2½, 2½–5, 5–12, 12–24, 24–36 inches. The samples were air dried, and passed through a 2-mm. sieve. The weight of the $>$ 2 mm. fraction, including stones and pebbles, was

recorded.[1] All analyses, except where otherwise specified, refer to the fine-earth material.

Bulk density[1] (apparent density) samples were also taken by means of a Uhland sampler, permitting the analytical data to be calculated in terms of amounts per unit volume and amounts per 36 in. profile. This type of data is given in graphical form only, using a column of 0·05 sq. ft. (approximate cross-section area of sampling tool) cross-section as the unit. Conversion factors to other convenient units: 215 x = g./m.^{2}, 1920 x = lb./A.

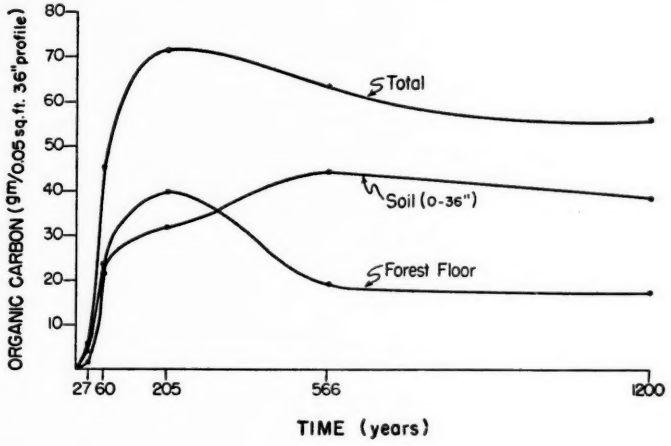

FIG. 5.

Organic carbon

The organic carbon content of the soils of the Shasta chronosequence was determined by means of the chromic acid oxidation method (Walkley and Black, 1934). Together with total nitrogen (A.O.A.C., 1940) and the C/N ratios the results are presented in Table 2. While the samples which were taken as representative of parent materials contained less than 0·02 per cent. carbon, values of more than 5 per cent. were attained in 205 years as a result of soil-forming processes.

The amounts of organic carbon per profile are plotted against the age of the system in Fig. 5. The curve for the forest floor increased rapidly to a maximum at the 205-year stage and then declined to half the amount in the two older members. The curve for the 36-in. soil profile increased rapidly in the 27–60-year period, almost keeping pace with the forest floor. This rapid rise in soil organic carbon is undoubtedly related to the great increase in quickly decomposable leaf-litter supply during this time. The soil carbon increased less rapidly during the 60–205-year period, but in the 205–566-year period it increased rapidly again to a still higher level. It is notable that the total carbon profile did not increase after the 205-year stage and that the principal change

[1] To be reported in the following paper in the series.

in the 205–566-year period was a redistribution of the carbon from the forest floor to the soil. It is interesting, however, that the carbon content of the upper foot of soil did not change appreciably after the 205-year mark, so that the above redistribution took the form of a downward extension of the carbon profile. It seems most likely that the principle mechanism of this process was downward movement of colloidal organic matter, although undoubtedly decaying roots also contributed.

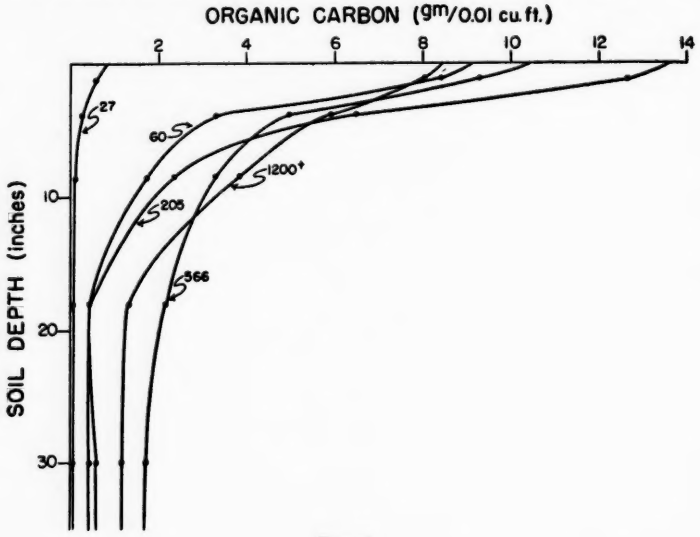

FIG. 6.

The downward extension of the carbon profile is further illustrated by the depth functions (Fig. 6). The most general feature to be noted is that there was no sub-surface horizon of accumulation such as one finds in a podzolized soil. The organic matter appeared to diminish more or less gradually with depth from a high value at the surface. The samples for the two older soils did not completely account for the whole profile as the values at the 24–36-in. level were still well above those of the parent material, and this accounts for the slight downward trends of the graphs for the older time states in Fig. 5.

Nitrogen

The amounts of nitrogen per profile are plotted against time in Fig. 7. The curves here have the same shape characteristics as those for organic carbon, but the differentiation between the forest floor and the soil is of a different order of magnitude. In contrast to the carbon, the soil accumulated nitrogen at a greater rate than the forest floor at all stages of the sequence. This was to be expected, of course, since the seat of nitrogen fixation is mainly in the soil, whence nitrogen moves into the plant and then to the forest floor at some low order of efficiency. On the other hand, the seat of carbon fixation is in the plant from which

TABLE 2

Organic Carbon and Nitrogen Data on Soils of the Shasta Chronosequence

Soil age depth	*Carbon %*					*Nitrogen %*					*C/N ratio*				
	27	*60*	*205*	*566*	*1,200+*	*27*	*60*	*205*	*566*	*1,200+*	*27*	*60*	*205*	*566*	*1,200+*
0–2½	0·17	2·72	5·65	5·41	4·61	0·012	0·148	0·260	0·245	0·175	14·1	18·3	21·7	22·1	26·1
2½–5	0·07	1·08	2·05	2·74	2·95	0·007	0·066	0·098	0·135	0·134	10·1	16·4	20·9	20·3	22·0
5–12	0·04	0·57	0·73	1·81	1·85	0·006	0·035	0·049	0·091	0·112	7·3	16·3	14·0	19·9	16·5
12–24	0·02	0·12	0·11	1·00	0·61	0·003	0·010	0·013	0·054	0·045	7·3	11·8	8·5	18·5	13·5
24–36	0·01	0·12	0·17	0·84	0·65	0·002	0·010	0·013	0·038	0·042	6·0	12·3	13·1	22·1	15·4

it moves directly to the forest floor. Nevertheless, as with the carbon, there was a considerable redistribution of nitrogen from the floor to the soil after the 205-year mark.

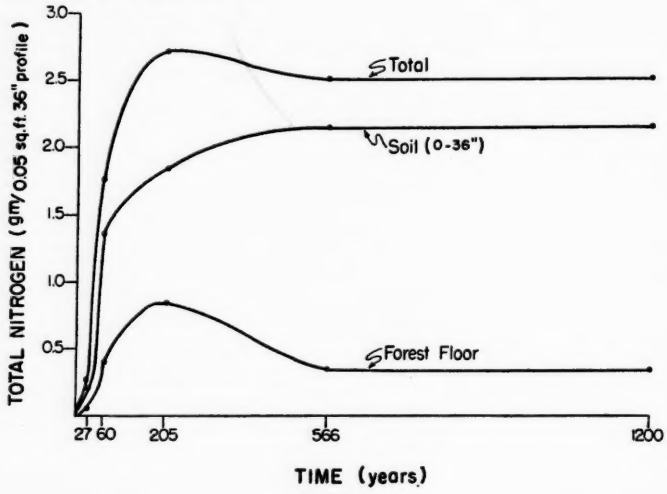

FIG. 7.

In the two oldest members of the sequence, which are thought to approximate a steady state, three-fourths of the carbon resided in the soil and one-fourth in the forest floor. By contrast, nine-tenths of the nitrogen was in the soil and one-tenth in the forest floor. These figures correspond to those found under pine in the Sierra Nevada mountains by Jenny (1950).

The depth functions for nitrogen (Fig. 8) show essentially the same characteristics as those for the carbon. The differences which exist are brought out in the data on carbon-nitrogen ratios. As with organic carbon, the inadequacy of the 36-in. profile to account for all the nitrogen, is also apparent. It is not unlikely that, had the profiles been sampled to greater depths, total nitrogen per profile would have continued to increase to the most advanced state of our investigated system.

The carbon-nitrogen ratios of the soil

It has been generally considered that the C/N ratio for soils of temperate regions tend to approach a value of 10 (Robinson, 1936). For forest soils a value of about 20 has been found more common (Lutz and Chandler, 1946). In this study the ratio for the 36-in. profile tended to approach a level of 18 to 20, after rising very rapidly in the first 60 years from an initial value of about 6 (Fig. 9).

The ratio for each profile varied greatly with depth (Fig. 10). In general, the ratio was higher at the surface and diminished with depth, although the three older soils showed a slight tendency towards higher values at the 24–36-in. level. The notably high values in the subsoil

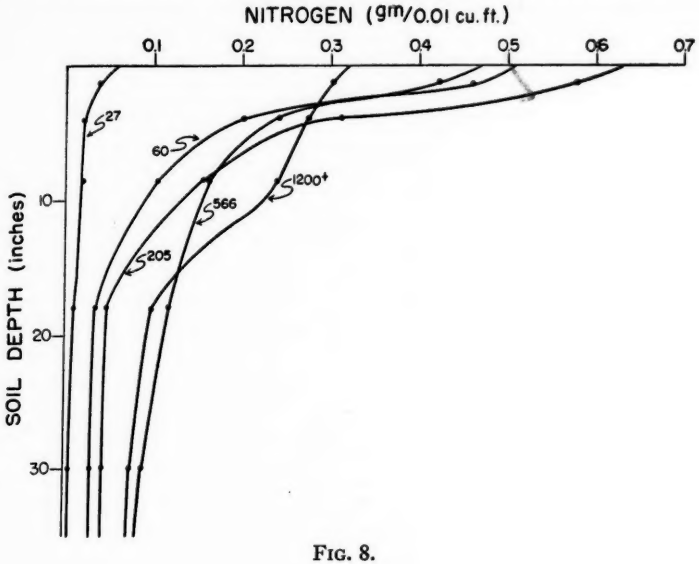

FIG. 8.

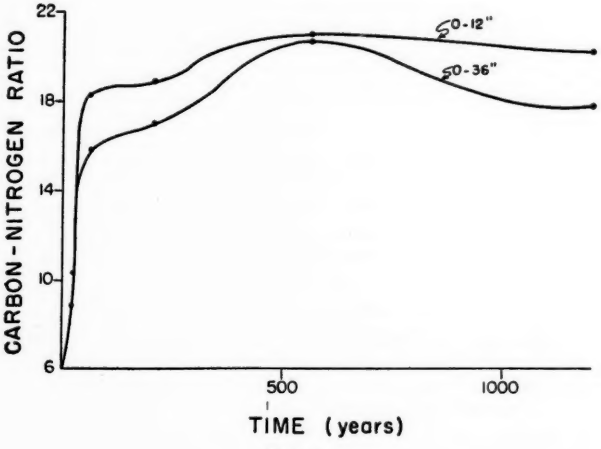

FIG. 9.

of the 566-year soil are due to the higher carbon content (Table 2), and probably reflect an aspect of the carbon redistribution, referred to above, which is not yet completed relative to the more rapid redistribution of nitrogen. No ready explanation could be found for certain of the irregularities in these depth functions, but it is obvious that errors of sampling can be greatly exaggerated by presenting data in the form of ratios.

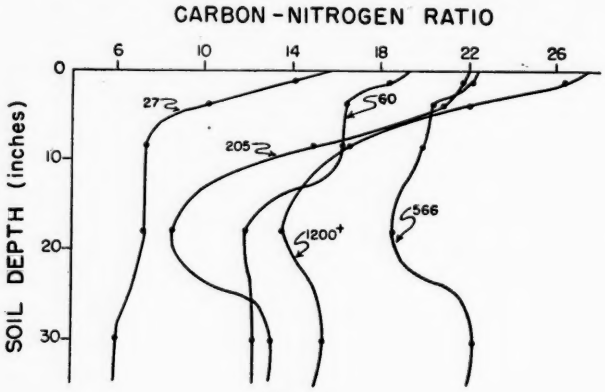

FIG. 10.

Discussion

The development of the organic profile outlined in the preceding sections proved to be a most important feature of the sequence, for the time functions of a great many of the other soil properties to be reported subsequently appear to be directly or indirectly related to it.

The relatively rapid build-up of nitrogen in the soils of the chronosequence, 0·15 per cent. (3,360 lb./acre) in 60 years, is interesting. An investigation of the mechanism of nitrogen fixation and accumulation in these mudflows would certainly be worthwhile, but this was not attempted in the present study. Since the parent material was essentially devoid of organic matter and since there was a general absence of legumes, the usual explanations of nitrogen fixation did not seem to be adequate. Of the alternative mechanisms non-symbiotic fixation seems most likely. This could include adsorption from the atmosphere in the manner demonstrated by Ingham (1950). Once a few plants became established and commenced photosynthesis, an energy source for microbial activity in the soil would become available through the leaf litter which began to accumulate almost immediately. According to Ingham's (1950) view this litter and its decomposition products would also increase the direct adsorption from the atmosphere. The reported presence of root nodules (Arzburger, 1910) on a number of species of *Ceanothus* may also be a factor, but would hardly explain the establishment of pines and *Purshia* in the sparsely inhabited 27-year member. The flourishing character of the pines as compared to other species suggests also that the effectiveness of mycorrhiza should merit examination.

As development proceeds, it is probable that plant roots extended down to buried soils underneath and obtained some additional nitrogen in this way, but neither the extent nor the rapidity of depletion of nitrogen (Dickson, 1952) in the buried soils, much of which must have been due to leaching out of the system anyway, would in itself account for the mechanism of accumulation in the surface soil.

The level at which the total organic profile became apparently stabi-

lized was determined by the particular set of ecosystem determining factors present. In comparing Sierra Nevada and tropical forest soils, Jenny (1950) speculated as to the relative importance of the climatic and biotic factors as determinants of the differences he found. In this study there were no means available for distinguishing the importance of the several factors in this matter. The sandy nature of the parent material and the lack of any immediate water-table suggested excellent aeration conditions were present. This was apparently more than off-set by the climatic conditions. Very favourable temperatures for microbiological decomposition do not occur until the beginning of the summer season when micro-organism activity is probably inhibited through lack of moisture. The strong acidity of the litter probably favoured initial decomposition by fungal organisms. As the organic matter changed in character and moved downward, first to the F-layer and then into the soil, the pH gradually increased, becoming more favourable to other types of microbial activity. The pH gradient, established by the deposition of acid litter (pH 4·2–4·5) on the mudflow material (pH 6·2–6·5), probably played a very significant role in determining both the ultimate level of stabilization and the differentiation of the organic profile.

Certain aspects of the relationship of forest development to forest floor and soil organic matter accumulation were also of interest. The trees of the 27-year forest bore fully leafed branches almost to ground level and consequently the leaf drop would be confined to old leaves. The very heavy leaf drop in the 60-year forest, however, was of a different character. In the 27–60-year period the growing pine-trees reached an overcrowded condition, resulting in an abnormally early abscission of nearly all leaves except those of the upper branches. This resulted in a greater accumulation of organic matter in both forest floor and soil than might otherwise be expected at this stage. Owing to the nature of the material (i.e. leaves), the total exchangeable base content of the profile reached a maximum at this point, as will be shown in a later paper. In the 60–205-year period the character of the organic matter accession to the forest floor and soil was undoubtedly of a much more woody nature, since it was estimated that 72 per cent. of the pine-trees in the 60-year forest were doomed to decomposition. This activity, however, must have taken place soon after the 60-year point, probably resulting in a somewhat greater forest floor maximum than is actually shown in Fig. 2. By the 205-year mark this decomposition activity had all but subsided, and although the organic matter of the total profile increased further, this material did not greatly enhance the amount in the mineral soil. From the 205-year stage on the plant succession appeared as a more or less steady development towards a mature forest in which there probably were no further drastic changes in the rate of accession of organic matter to the forest floor and soil.

Summary

The development of the forest floor and the total organic carbon and nitrogen profiles of the Shasta chronosequence were described and discussed.

The mass of the forest floor reached a maximum in 205 years and then declined to nearly half the amount at the 566 and 1,200+ points. The accession to the forest floor of pine needles in the 27–60-year period and of tree limbs and trunks in the 60–205-year period was much greater than in any other periods of the sequence.

The time functions of organic carbon and nitrogen profiles approached apparent steady state values within 566 years. Although the total carbon attained this value at 205 years, there followed a pronounced redistribution of carbon from forest floor to soil in the 205–566-year period. A similar redistribution of nitrogen also occurred. In the two older members, one-third of the total carbon and approximately one-eighth of the total nitrogen resided in the forest floor. The C/N ratio in the forest floor decreased from 107 to about 50, whereas that of the soil increased from 6 to about 20.

The interrelationship of forest development and the above trends have been discussed. The role of a pH gradient established by the deposition of an acid litter on the surface was indicated and the problem of nitrogen fixation and accumulation was pointed out.

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(Received 17 November 1952)

PLATE I

PLATE II

PLATE III

PLATE IV

THE BIOLOGY OF FOREST SOILS WITH SPECIAL REFERENCE TO THE MESOFAUNA OR MEIOFAUNA

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(*Rothamsted Experimental Station, Harpenden*)

WITH TWO PLATES

Introduction

Deer, jumping mice, and the oven-bird are denizens of the forest floor by virtue of using it as their substratum, but there is also a host of curious animals which use the forest floor, especially the litter of dead leaves, twigs, branches, and fruit parts, as their walls, ceiling, and sub-basements. Looked at from the eye-level of the cockroach, this litter becomes a several-story edifice of enormous extent. The various floors are separated by twigs, midribs, petioles, fruit husks, samaras, skulls, elytra and faeces. The lower one descends, the more compact is the structure. The leaves become more fragmentary, the faeces of worms which have come up from the soil, of caterpillars which live in the trees and of the inhabitants themselves, as well as grains of sand brought up by the worms and a heterogeneous assortment of beetle skulls and wing covers, become more abundant. This complex is rendered more intricate by the growth of minute fungus moulds which feed upon the dead leaves and organic refuse, weaving it all into a compact mat by their myriad white hyphae. Thus is the woof woven into the warp of the woodland rug.

In these words the late Dr. Jacot (1935) has sketched a brilliant picture of the teeming life which exists in the forest floor. The term 'soil fauna' naturally refers to all forms of animal life which at some stage in their life-history live on or within the soil. Workers in the field of soil biology have divided this fauna into three groups: micro-, meso-, and macro-fauna (Fenton, 1947). These highly arbitrary groupings, a *modus vivendi* suitable to the present state of our knowledge, are based partly on size and partly on methods used for assessment and study. Recently Van der Drift (1951) has suggested a more precise grouping with four categories, but as his scheme is based strictly on size, it is difficult to apply with the techniques available.

Bearing in mind the inadequacy of present methods, the mesofauna can be defined as those organisms collected by the funnel method of extraction, and include the Arachnida, Myriapoda, and Insecta, members of the phylum Arthropoda, and frequently described as micro-arthropods. In size they range from the smallest mites approximately 100 μ long to insects such as the larger Collembola which may be 1 cm. in length. The writer (1950) would prefer the term meio- instead of meso-fauna as the transition from micro- to meso-fauna is much more gradual and less easily defined than that from meso- to macro-fauna. The proposed terminology corresponds with Mare's (1941–3) classification of the bottom fauna of the sea. The term 'mesofauna' does not in fact describe a middle group, but a population more closely allied to the larger micro-organisms and with the additional important distinction that they live in existing soil pores and interstices, and usually cannot create additional living space through burrowing activity. Unlike their

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larger brethren, they cannot influence the mechanical structure of their medium. It is unfortunate that these terms are frequently used rather loosely; indeed there is a strong case for a more precise delineation of the basic groupings if only to assist the reader when referring to papers in other languages.

Ever since Darwin's (1883) famous work *The Formation of Vegetable Mould through the Action of Worms, with Observations on their Habits*, writers have speculated on the importance and influence of soil organisms on their medium. Of the many characteristics of the soil as influenced by its biomass that receiving most attention has been organic-matter status and distribution. P. E. Müller (1879, 1884), with his acute powers of observation, first drew the forester's attention to the very distinct humus formations, mull and mor. He found and recorded not only differences in vegetation, soil structure, and chemical composition but also observed and was greatly impressed by the faunistic differences occurring under these conditions. Müller considered that the principal agent in mixing organic material with the mineral soil—the characteristic of mull—was the earthworm. In mor, on the other hand, earthworms are absent as a rule, and consequently the organic matter forms a discrete layer on the soil surface. Soil type, with some exceptions, does not directly influence the formation of mull or mor or the infinite gradations occurring between these extreme conditions, but rather exercises an indirect influence, inextricably merged with vegetation type (litter source) and physiography of the site.

Many have followed in Müller's footsteps and have examined the litter, humus, and soil layers of the forest in order to identify and record the kinds of organisms found there. In 1905 Berlese published a paper describing an apparatus for separating organisms from soil or other material, and this apparatus, now known as the Berlese funnel, proved a great advance on existing techniques. Since that date there have been many modifications, the most important being Tullgren's (1918) substitution of an electric-light bulb as the desiccating principle instead of the hot-water jacket of the original apparatus. Thus the Berlese funnel, or more correctly the modified Berlese funnel, method is based on the movement of the population under the influence of light (influence small) and gradual desiccation of the medium containing them. Typically the apparatus is arranged in the form of a funnel over which the sample is placed, in a sieve, and the organisms move downwards and are collected in a phial placed beneath. Many soil-faunal surveys have been carried out using this apparatus, and with results which are a great improvement on earlier investigations. The writer (1950) has devised a modification known as the split-funnel extractor which overcomes some of the difficulties of the more traditional methods. However, even the latest modifications do not extract all the Acari or Collembola, and though other processes have been used, none has proved wholly successful. For example, flotation methods, valuable under agricultural conditions, are rarely suitable for samples from forest sites owing to their high organic-matter content (Evans, 1951). The crux of the matter is the difficulty of finding a method with a common denominator to em-

brace the diversity of animal life present. It is very difficult to devise a method with a physical, chemical, or biological basis which will have the desired effect on all organisms. Theoretically, a method involving some physical factor should prove most successful; in practice this is not necessarily the case. As a general rule the most successful faunal surveys are those devoted to a specific organism, usually one injurious to plant or animal life.

Quantitative Aspects of the Soil Faunal Population

Table 1 gives some indication of the more important quantitative surveys of the meiofauna and macrofauna of forest habitats; it will be seen that the majority refer to European countries. It does not pretend to cover all the quantitative investigations carried out since 1900, and does not include surveys of single groups of organisms as, for example,

TABLE 1

Principal Quantitative Soil Faunal Surveys of Forest Habitats since 1900

Author	*Date of publication*	*Country*
Europe (excluding Russian literature)		
Diem, C.	1903	Switzerland
Pillai, S. K.	1922	Germany
Pfetten, J. von	1925	,,
*Soudek, S.	1928	Czechoslovakia
Trägårdh, I.	,,	Sweden
*Bornebusch, C. H.	1930	Denmark
*Ulrich, A. T.	1933	Germany
Noordam, D., Jr. *et al.*	1943	Holland
Forsslund, K. H.	1944–5	Sweden
Jahn, E.	1950	Austria
*Van der Drift, J.	1951	Holland
U.S.A.		
Jacot, A. P.	1936	North Carolina
*Lunn, E. T.	1939	Illinois
Eaton, T. H., Jr. *et al.*	1942	New York
Pearse, A. S.	1946	North Carolina
Others		
Grimmett, R. E.	1926	New Zealand
*Williams, E. C., Jr.	1941	Panama
Strickland, A. H.	1945–7	Trinidad, British West Indies

* Include biomass estimations.

Agrell's (1941) study of the Collembola of Swedish Lapland. An examination of this literature reveals some interesting differences between the approach of European and American investigators. Whereas the former are much concerned with the activity and functions of these creatures, American ecologists have approached the problem from a population-dynamics viewpoint with the object of relating soil populations to those occurring above ground, and using them as an exercise in community study to elucidate some of the extremely complex

TABLE 2

Soil Faunal Studies carried out in the United Kingdom

(These surveys are quantitative unless otherwise stated)

Author	*Date of publication*	*Experimental site*	*Habitat*	*Method*	*Remarks*
Cameron, A. E.	1913	Manchester, Lancashire	Grassland	Hand sorted	Insecta only. Not quantitative
Cameron, A. E.	1917	Holmes Chapel, Cheshire	,,	,,	Insecta only
Morris, H. M.	1920–1	,, ,,	,,	,,	,,
Buckle, P.	1921	Northenden, Cheshire; Bury, Lancashire	Arable and grassland	Dry sieved	Not quantitative
Morris, H. M.	1922	Rothamsted, Hertfordshire	Arable land	Hand sorted	Approximate biomass estimated
Thompson, M.	1924	Aberystwyth, Cardiganshire	Grassland	Wet sieved and flotation	..
Morris, H. M.	1927	Rothamsted, Hertfordshire	Arable land	Wet sieved	..
Edwards, E. E.	1929	Aberystwyth, Cardiganshire	Arable and grassland	Wet sieved and flotation	..
Ford, J.	1935	Wytham near Oxford, Berkshire	Grassland	Vegetation: Berlese funnel Soil: flotation	Very large populations Collembola

Ladell, W. R.	1936	Rothamsted, Hertfordshire	Arable land	Ladell flotation	..
Ford, J.	1937–8	Headington near Oxford, Oxfordshire	Grassland (*Bromus erectus* Huds.)	Berlese and Tullgren funnels	Above ground vegetation only sampled
Baweja, K. D.	1939	Rothamsted, Hertfordshire	Cultivated soil later sown to grass	Ladell flotation	Effect of partial soil sterilization on soil organisms
Glasgow, J. P.	1939	Slough, Buckinghamshire	Grassland	,,	Collembola only
Jones, J. M.	1939	Aberystwyth, Cardiganshire	Garden soil	,,	..
Rayski, C.	1945	Edinburgh and other parts of Scotland	Hill pasture	Tullgren funnel	Oribatei only
Evans, A. C. *et al.*	1948	Rothamsted, Hertfordshire	Grass, ley, and arable land	Potassium permanganate	Earthworms only. Biomass calculated
Guild, W. J. McLaren	1948	Stirlingshire and Perthshire	Grass and hill pasture	,,	Earthworms only
Salt, G. *et al.*	1948	University Farm, Cambridge	Grassland	Salt and Hollick flotation	Very detailed examination of a small number of samples
Macfadyen, A.	1952	Cothill, Berkshire	Fenland	Tullgren funnel	Acari and Collembola. Biomass estimated

problems of interaction between groups of organisms living in a common environment. This ultra-synecological approach appears a premature step, and one that is not enhanced by the rather indifferent techniques employed. Of the surveys quoted in Table 1 the most comprehensive are those of Bornebusch, Ulrich, Forsslund, and Van der Drift.

TABLE 3

Total Populations of Soil Arthropoda in Heathland and other Habitats in the United Kingdom

Habitat	*Total sample depth*	*Numbers per sample*	*Numbers per m.²* (*thousands*)	*Numbers per acre* (*millions*)	*Numbers per c.c.*	*Sample volume* (*c.c.*)
Natural heathland (maximum) . .	11⅜ in.	998	569·7	2,305	1·97	506
Cultivated heathland with trees (maximum)	11⅜ in.	1,462	834·5	3,377	2·89	506
Fenland* . . .	2 in.	159	159·4	645	3·18	50
Grassland† . . .	12 in.	2,756	340·5	1,378	1·15	2,471
Arable land‡ . .	9 in.	201	25·9	105	0·11	1,770
Garden soil§ . .	9 in.	306	39·5	160	0·17	1,770

* Macfadyen, A. (1952): Mean of 120 samples obtained at monthly intervals from Sept. 1949 to Aug. 1950 from *Molinia caerulea* (L.) Moench tussocks in advanced fenland at Cothill, Berkshire. Tullgren funnels used. Population numbers refer to Acari and Collembola, and of these only the most abundant species are included. Dominant plants *Molinia caerulea*, *Juncus subnodulosus* Schrank, and *Deschampsia caespitosa* L. occupying approximately 10%, 7%, and 5% of the area respectively. Figures in table therefore represent mean populations in *Molinia* tussocks and not that of area as a whole. Numbers recorded from *Juncus* and *Deschampsia* much smaller.

† Salt, G., Hollick, F. S., Raw, F., and Brian, M. V. (1948): Mean of 9 samples (Nos. 12–20) obtained Nov. 1943 from old-established grassland near Cambridge. Flotation extraction.

‡ Baweja, K. D. (1939): Mean of ? samples obtained at monthly intervals from Jan. 1936 to Mar. 1937 from 8 sterilized plots at Rothamsted. Ladell flotation used. Soil had been partially sterilized by baking in an oven. Plots later sown with rye grass (*Lolium perenne* L.). Figures quoted in table do not include populations of control plots.

§ Jones, J. M. (1939): Mean of 18 samples from 6 plots in the experimental garden attached to the University College of Wales, Aberystwyth, obtained on three occasions between Nov. 1938 and Feb. 1939. Each plot sampled once on each sample date. Flotation extraction. Five plots in fallow, the sixth contained rhubarb (*Rheum rhaponticum* L.).

Soil faunal surveys in the United Kingdom (Table 2) have been concerned mainly with the grassland biome. This is partly due to the subordinate position of forestry in this country in the past, and partly to the lead given by such pioneers as Cameron and Morris who concentrated on agricultural habitats. Another noticeable feature is the method of extraction employed. In many cases separation has been achieved by a sieving method, in the early days a simple wet-sieving technique and leading up to the elaborate flotation process used by Salt and his co-workers. Table 3 compares the most recent British figures for arthropod organisms from natural and cultivated heathland (with trees), fenland, grass, arable, and garden soil. The numbers per acre bear little

value but have been included for comparison, as in the past it has been customary in surveys of this nature to indicate populations in terms of this area. A most striking feature is the large numbers present in heathland and the meagre numbers in cultivated sites. The heathland figures are believed to be the highest yet recorded in Britain. It should be stressed, however, that the latter represent populations occurring in November at a time when they tend to build up to a peak; they do not indicate the mean of numbers recorded over a period, as for example is the case with the fenland figures. The small populations of arable land may be a reflection of technique, although there is a general impression that soil disturbance causes major reductions. Again, the fenland figures represent the Acari and Collembola components only, occurring in *Molinia caerulea* (L.) Moench tussocks which cover about 10 per cent. of the area; the populations of the other dominant plants are much smaller. It would be unwise to attach too much importance to the data of Table 3 as there is not yet sufficient information to provide a comprehensive picture of population numbers. They are tabulated as the best at present available and indicate the order of magnitude to be expected in such situations.

Owing to the dearth of surveys of forest habitats in this country, one must turn to continental workers for information of the number of organisms present in various forest types. Table 4 outlines the populations of meiofauna and macrofauna in beech on mull and beech and spruce on mor. The small number of surveys tabulated is due to the difficulty of comparing data because of different methods of expressing population numbers, and even in these examples there is a degree of approximation owing to this feature. There is no doubt that a standard method of presentation to allow of comparisons is highly desirable, and indeed essential, if the greatest possible information is to be obtained from this arduous form of research.

The data of Bornebusch (1930) and Ulrich (1933) represent early investigations using similar techniques and are best considered together. It will be noted that there are considerable differences in the population totals recorded by these investigators; this is especially so in the beech mull where the figures are 0·06 and 1·94 per c.c., respectively. Apart from possible site and geographical differences, there are two plausible reasons for these discrepancies. Bornebusch took very large samples of 10–17 cubic decimetres and these would favour the macrofauna which in fact form 29 per cent. of the total. In addition large samples would militate against the recovery of mites and springtails, and Trägårdh and Forsslund (1932) have suggested that his numbers represent 10 and 2 per cent. of these groups, respectively. However, it is unlikely that the Collembola have been reduced to this level, as will be demonstrated later. The spruce-mor figures show close agreement in the percentages of Acari and Collembola (see Table 6), which suggests that here the reduction in numbers is more evenly distributed over these animal groups. Forsslund's (1944–5) and Van der Drift's (1951) surveys give a clear indication of the quantitative limitations of earlier work. The former's population is the mean of two samples, representing a total of

TABLE 4

Total Populations of Meiofauna and Macrofauna in European Forest Habitats

Author	*Habitat*	*Total sample depth*	*Numbers per sample*	*Numbers per m.²* (*thousands*)	*Numbers per c.c.*	*Sample volume* (*c.c.*)
Bornebusch, C. H. (Denmark)	Beech mull	4 in. (?)	619	6·2	0·06 (?)	10,000 (?)
	Beech mor	6½ in. (?)	1,943	19·4	0·11 (?)	17,000 (?)
	Spruce mor	5 in.	1,194	11·9	0·09	13,000
Ulrich, A. T. (Germany)	Beech–oak mull	..	1,938	..	1·94	1,000
	Spruce mor	..	2,260	..	2·26	1,000
Forsslund, K. H. (Sweden)	Spruce–pine–birch mor	4 in.	1,184 1,430	1,089·6	10·90	400 100
Van der Drift, J. (Holland)	Beech mor	1½ in.	1,033 214	336·5	8·79	40 4,000

Numbers per m.² × 4,000 = approximate numbers per acre.

Notes

Bornebusch, C. H. (1930): Figures approximate, as Bornebusch does not always state depth of litter layer, and depth of mull soil sampled not precisely defined. Worms sampled to 25-cm. depth, but this is not taken into account in calculating sample volumes. Tullgren funnel used.

Beech mull: Mean of 9 samples obtained at approximately 3-month intervals between Aug. 1926 and Nov. 1927 from locality 15. 80-year-old beech (*Fagus sylvatica* L.) interspersed with *Larix decidua* Mill., 125 years old. Ground flora *Anemone–Asperula* type.

Beech mor: Mean of 4 samples obtained at 2–3-month intervals between Mar. and Nov. 1927 from locality 20. Only litter and raw humus sampled. Beech, no ground flora. Thick layer of litter, but depth not stated.

Spruce raw humus: Mean of 12 samples obtained at approximately 2-month intervals between Mar. 1926 and Nov. 1927. Only litter and raw humus sampled. 72-year-old spruce stand, ground flora moss. Litter layer 5 cm.

Ulrich, A. T. (1933): Mean of 12 samples obtained from each habitat at monthly intervals between Aug. 1925 and Aug. 1926. Only litter and raw humus sampled. Tullgren funnel extraction. Sample areas 68-year-old beech–oak and 100-year-old spruce in stands adjoining one another. Samples measured by volume. Depth of horizons sampled not clear and thus impossible to calculate density per square metre. Volume figures quoted depend on accuracy of sampling method.

Forsslund, K. H. (1944–5): Mean of 2 samples (Nos. 3 and 4) obtained July 1936 from locality II. Litter samples extracted with Tullgren funnel; raw humus, Berlese funnel. Spruce–pine–birch with light stand density, dating back to 1866, when area devastated by forest fire. Ground vegetation *Vaccinium* type with *V. myrtillus* L. and *V. vitis-idaea* L.; herbs and grasses rare. Litter layer weakly developed, well-demarcated F and H horizons. Samples taken and results presented on volume basis. Above figures calculated from profile dimensions. Sample No. 3 a normal population, but sample No. 4 represents greatest number obtained during investigation.

Van der Drift, J. (1951): Only litter and raw humus sampled. Samples measured by volume without reference to area. Areas occupied by equal volumes of the various layers ascertained for a small number of samples, and from this data factors calculated to convert number per unit volume to unit area. These values have high standard deviations, and Van der Drift stresses that they represent rough approximations of the average composition of the forest floor and may err to the extent of 20–40% of the calculated values. Thickness of litter and raw humus layer varies from 1–8 and 1–4 cm. respectively. Estimated mean values equal 0·65 and 3·3 cm. Area sampled, 85-year-old beech (*Fagus sylvatica* L.) stand (plot 8 G). A few small oaks interspersed amongst beeches. No ground flora. Two types of sample taken:

1. Mesofauna: Animals 0·1–2·00 mm. Includes all Acari and Collembola (except Entomobryomorpha). Sample 40 c.c. Figures represent mean of 5 samples (litter layer mean of 2 samples) obtained at irregular intervals between May 1944 and Mar. 1946. Sample dates yielding low numbers have been omitted by Van der Drift in order to obtain a mean of 'normal' populations. Above figures are calculated from this mean.
2. Hemiedaphic macrofauna: Animals > 2 mm., but omitting a few species which occurred during restricted periods. Sample size 4 c.dm. Figures are mean of 27 samples (litter samples somewhat less) obtained at irregular intervals between Jan. and Dec. 1946. Epedaphic macrofauna, such as beetles and other active surface creatures obtained by a trapping technique, have been omitted in calculating above figures.

4,410 million per acre, and in the writer's knowledge is the largest population recorded from any soil habitat. The writer has specifically chosen these samples to give some indication of the numbers that may be expected from forest soils with improving methods. Van der Drift's total of 8·79 organisms per c.c. is 4 times greater than Ulrich's and 80

times greater than Bornebusch's figures, though it is probable that his mor with a 4-cm. layer of litter and raw humus is less extreme than the equivalent sampled by Bornebusch, but this fact should if anything favour larger numbers in the latter.

These investigations have the common feature of increasing population estimates with improving methods. Thus Bornebusch's maximum number of 79 million per acre is rendered insignificant by Forsslund's formidable total of 4,410 million per acre. Yet despite the large totals of Tables 3 and 4, under certain conditions they may be gross underestimates of the actual density. Forsslund (1947) has examined directly small samples from Swedish forest sites and has obtained a population equivalent to 2,300,000 arthropods per square metre. Whilst it would be unwise to regard this as a true estimate owing to the methods used in sample selection, &c., it represents a twofold increase on the maximum figure already quoted.

A figure expressing population per unit area, although an important measurement (Macfadyen, 1952), can be misleading, as will be quickly realized if the numbers per unit volume of the soil matrix are considered.

The maximum concentration in Tables 3 and 4 (apart from Forsslund's figure) is 8·79 per c.c. (Van der Drift), although his numbers rank fifth in a descending scale of density per unit area. Theoretically the ideal quantitative relationship is one based on the total volume of interstices and pores of the soil (or better still the surface areas of these spaces), as has been pointed out by Stöckli (1946), Weis-Fogh (1947–8), Van der Drift (1951), and others. Unfortunately this is a difficult physical measurement, and determination of surface area is at present impossible. One compromise is to relate density to weight of medium, but owing to the great differences in volume weights of organic material (raw humus approximately 0·2) and mineral soil (approximately 1–1·5), such figures have little meaning except perhaps in the litter layer. At the present time the only basis in most cases is to refer the population to the area sampled, and *indicate depth to which sample refers.*

With the natural heathland figures (Table 3), however, it is possible to get some indication of the actual spatial relationships as pore-space measurements are available (Rennie, 1951; see Table 7). If the population in the raw-humus horizon is considered alone, the litter layer being excluded, the numbers per c.c. of pore space (75 per cent. of the gross volume) are 9·9. But as 66 per cent. of the pore space contains water during the greater part of the year (Rennie, 1951), and assuming that these creatures cannot exist for long under such conditions, the volume of pore space available to the population referred to in Table 1 and Fig. 1 is 7 c.c., which represents a density of 82·2 per c.c. of gas-filled pore. As the pore space of mineral soil is normally about 40–55 per cent. (range 30–65 per cent.), the gross volume figures $\times 2$ will give an indication of the numbers per unit volume of living-space. The greater pore volume (70–90 per cent.) of raw humus may partly explain the large numbers often present under mor conditions for the simple reason that suitable living-space is not exerting a limiting influence.

FIG. 1. The vertical distribution of soil arthropods in natural and cultivated heathland (planted with *Picea sitchensis* Trautv. and Meyer). The graph on the left illustrates the distribution of a mite belonging to the Acaridiae in the natural heathland. Sample in each case is a cylinder $1\frac{7}{8} \times 11\frac{3}{8}$ in. deep with a volume of 506 c.c.

The litter layer can hardly be dealt with in this way, as Ford (1938) and Van der Drift (1951) have pointed out. The interstices are much larger, and for the smaller creatures, at least, the area of surface available is the most important criterion. This is obviously a difficult determination, and here weight might be used as the best compromise. Ford (1938) attempted to measure the area available in the litter of his *Bromus* tussocks habitat and obtained a value of 296 sq. cm. per g. of dry grass. Allowing 0·25 sq. mm. as the area occupied at any one moment by single inhabitants, he estimated that at the period of greatest density each individual had a territory 2,600 times its own area available to it. He makes the interesting analogy that if one square yard is allowed per stationary man, the population of the Brometum at its greatest density is rather less crowded than are the inhabitants of Belgium.

The population number per unit volume of substrate provides a mean value for the profile; the fauna, however, is not distributed uniformly but shows a marked zoning which is primarily dependent on the factors living-space, oxygen and water status, and food supply. All soils have the greatest faunal concentration in the surface layers, a characteristic which is most marked with mor-humus distribution. In grassland, on the other hand, there is not the same sharp demarcation between surface and deeper horizons, and it is probable that good examples of this habitat have a high density below 6 in., but unfortunately the quantitative data available are not sufficient to prove the point.

The vertical distribution in heathland will serve as an illustration of the situation under mor conditions. Fig. 1 contrasts the total population occurring in natural heathland (Allerston Forest area, east Yorkshire) with that occurring in cultivated heathland planted with Sitka spruce (*Picea sitchensis* Trautv. and Meyer; trees 20 years old and forming canopy). The populations are those quoted in Table 1. The natural heathland profile, somewhat simplified, is a podzol with a shallow litter and raw-humus horizon (total about 2 in.), and a very distinct, thin iron pan occurring some 6½–7 in. below the surface. The dominant vegetation is *Calluna vulgaris* Salisb. The totals in the various horizons should be treated with caution owing to the great variation from sample to sample. They should be regarded merely as a broad indication of the vertical population structure.

The most obvious property of this distribution is the great compression in the natural heathland, 96 per cent. (9·6 per c.c.) of the population being concentrated in the first 2¼ in. The remaining 4 per cent. (0·1 per c.c.) is scattered through the profile and shows no local concentrations except in the organic matter just above the pan. The maximum density, 28·1 per c.c., occurs in the first ¼–½ in. of the raw-humus horizon; this would correspond to Hesselman's F layer, though it is not always possible to differentiate F and H layers in this particular mor. This result agrees with the findings of Forsslund (1944–5) and Van der Drift (1951), the latter's maximum density being 17·6 per c.c. in his F layer compared with 8·8 per c.c. of the profile as a whole. The distribution in the cultivated heathland is the result of rather special conditions and on that account will be considered later. The situation in grassland

as illustrated by the data of Salt *et al.* (1948) may be briefly referred to. Of the total population quoted in Table 3, 67 per cent. of the Acari and Collembola occurred in the 0–6 in. and 33 per cent. in the 6–12 in. zones. It is not possible to apportion the other arthropod organisms, but as they represent only 11 per cent. of the total their omission will not greatly influence these figures.

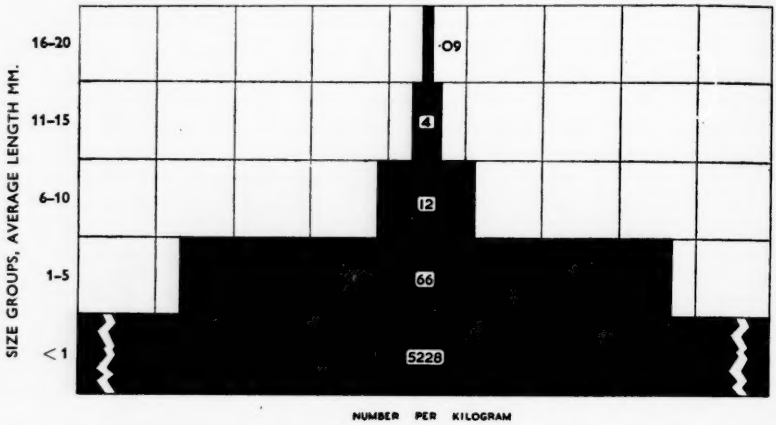

FIG. 2. Pyramid of numbers of the metazoan fauna of the forest floor of Carlé Woods, Illinois. (Park, Allee, and Shelford; after Allee *et al.*, 1949.)

A fundamental property of animal communities is the presence of large numbers of small creatures and a reduction in numbers with increasing size, and several investigators, for example Ghilarov (1944), have demonstrated this numerical relationship in the case of soil organisms. Thus a consideration of populations in terms of density of individuals can easily give a distorted or even erroneous impression of the animal community. This attribute can be best demonstrated in the Eltonian pyramid of numbers in which the population is segregated into trophic levels; the latter may correspond very broadly to the linear dimensions of the fauna. At the present time owing to the lack of knowledge of the food habits of many soil organisms, a pyramid can only be constructed on the basis of numbers of organisms in a series of arbitrary size-ranges. Fig. 2 illustrates the number/size relationship of the fauna of a forest floor in Illinois and shows clearly the negative correlation. Interdependence of these two properties is due to the generally higher reproductive potential of the smaller creatures and the fact that they form the food supply of the larger organisms. Assuming that this 'pyramid' broadly indicates the sequence of food habits, then the lower steps will represent the herbivores, the higher ones the carnivores. Of course the ultimate base consists of countless myriads of microfauna; Fig. 2 is merely a truncated diagram indicating the superstructure. In this connexion it is interesting to note that the size relationship of the population as a whole may be reflected also in the broader taxonomic

groups. For example, there is a tendency for small surface-feeding earthworms to occur in poor sites (especially forest habitats) with an increase in numbers of larger species under more fertile conditions. Further, there is a marked positive correlation between size of earthworm and depth of penetration in its medium.

Applying this characteristic to the habitats already discussed, we find a telescoping of the pyramid under heathland conditions. There is a greatly enlarged base and an attenuated superstructure representing the small number of large organisms, in many cases the predators of the primary population. In fertile sites the figure is horizontally compressed and the steps ascending the pyramid show more even reductions in length, the whole tending towards a more perfectly symmetrical pyramid.

To complete this discussion of the quantitative characteristics of the soil population it is necessary to consider briefly the biomass[1] of fauna, a measure necessary to integrate size and number, and thus provide a clearer conception of the living material available. Several investigators (see Tables 1 and 2) have attempted this measurement, but owing to the shortcomings of present experimental methods their results probably diverge from the absolute values to a considerable extent. Table 5 represents the biomass figures of the surveys already quoted in Table 4 with the addition of Macfadyen's figures from Table 3. The estimates in all cases are obtained directly by weight or measurement. Bornebusch, for example, weighed his material preserved in spirit. Ulrich in all cases, and Van der Drift in most, obtained their volumes by measurement. Macfadyen has used a method involving a combination of weight and measurement. Unfortunately it is not possible to compare directly his results with some of the other surveys as the data provided in his paper are not sufficient to enable one to convert his weight figures to volume values.[2] Bornebusch's totals, although too low on an absolute scale, provide an interesting illustration of the relative differences between mull and mor. Beech mull has a total of 70·8 g. per sq. m., of which 53 g. consists of earthworms. In beech mor the total is 16·6 g., and this reduction is primarily due to the small number of earthworms, which weigh about 1 g. per sq. m. It will be noted that the Acari and Collembola figure for mor is almost double that of mull, although the reservations already referred to in regard to numbers must be borne in mind. Ulrich's figures appear rather low (his method of estimation being probably the least accurate), though it should be remembered that as his beech–oak mull samples comprised litter only, he missed the large populations presumably present in the upper layers of the mull soil. His total biomass is close to Van der Drift's for beech mor, though the latter's figure for Acari and Collembola is very much higher. Macfadyen's total (mites and springtails only) is the lowest of the later surveys, and this might be expected, although the unusual structure of

[1] Biomass may be defined as the weight of a species population per unit of area (Allee *et al.*, 1949). Here it is used in a looser sense and covers volume and weight per unit area or unit volume, depending on data available.

[2] Mr. Macfadyen has since kindly informed me that his weights are in fact close to the volumes if one assumes densities are near 1.

TABLE 5

Biomass of Soil Meiofauna and Macrofauna in Various Habitats

(For details of sampling procedure, &c., see Tables 3 and 4)

Author	Habitat	*Total fauna*					*Acari and Collembola*					
		Biomass per sq. m.		*Numbers per c.c.*	*Biomass per c.c.*		*Numbers per c.c.*	*Biomass per c.c.*		*Mean biomass per individual*		*Approximate ratio of living matter to litter volume*
		Volume (c.c.)	*Weight (g.)*		*Volume (c.mm.)*	*Weight (mg.)*		*Volume (c.mm.)*	*Weight (mg.)*	*(c.mm.)*	*(mg.)*	
Bornebusch, C. H.	Beech mull	..	70·77	0·06 (?)	..	0·708 (?)	0·04 (?)	..	0·0029 (?)	..	0·0658	..
	Beech mor	..	16·57	0·11 (?)	..	0·097 (?)	0·10 (?)	..	0·0056 (?)	..	0·0560	..
	Spruce mor	..	9·84	0·09	..	0·076	0·08	..	0·0045	..	0·0558	..
Ulrich, A. T.	Beech–oak mull	..	..	1·94	0·266	..	1·84	0·032	..	0·0176	..	1:31,000
	Spruce mor	..	..	2·26	0·111	..	2·12	0·034	..	0·0162	..	1:29,000
Forsslund, K. H.*	Spruce mor	..	..	14·9	0·070	..	14·6	0·052	..	0·0047	..	..
Van der Drift, J.	Beech mor	11·20	..	8·79	0·283	..	8·61	0·087	..	0·0097	..	1:33,000
Macfadyen, A.	*Molinia* tussocks fenland	..	..	..	..	..	3·19	..	0·027	..	0·0085	..

* Forsslund, K. H. (1947): Not the same site as quoted in Table 4. Mean of 3 samples (Nos. 3A–5A) obtained from F and H layers excluding litter. Sample size and extraction as before. Locality V of 1944–5 survey. Spruce stand of *Vaccinium* type mixed with pine and broadleaved species. F and H layers together = 3·5–5·0 cm.

the fenland with 14 ft. of peat overlying the mineral stratum makes comparison with forest sites rather difficult.

The last column of Table 5 gives some indication of the spatial relationships of the litter fauna in terms of volume of litter material. These figures suggest the interesting conclusion that the total biomass of Acari and Collembola shows no great differences in the *upper litter* layers of beech mor and spruce (with reservations). Van der Drift's total for these groups in the litter and raw humus is equivalent to 1:11,000, and his maximum, which occurs in the F layer, 1:5,000. Macfadyen's ratio of 1:37,000 (assuming a sp. gr. of 1) indicates that the fenland biome compares rather unfavourably with the raw-humus layers of a beech forest.

Unfortunately there are no comparable figures for grassland, but Salt *et al.* provide some estimates which are worthy of attention. They suggest that the spatial relationships in their habitat may be represented by a large wireworm (Elateridae) at one end of the scale, with a ratio of 1 part by volume of living matter to 20 parts soil, and the smallest mites having an approximate volume of 0·0005–0·004 c.mm. which is equivalent to 1:2,000,000. Considering only the smaller creatures (mainly Acari and Collembola), they estimate an average volume per individual of 0·05 c.mm. (Van der Drift's corresponding mean volume per organism is 0·01 c.mm.), which is equivalent to 1 part of living matter to 20,000 parts of soil. When compared with the figures already quoted this seems a very reasonable estimate, and bearing in mind the sample depth of 12 in., probably points to a very much greater proportion of living material than would be present in a beech mor. To sum up, present data suggest the following proportions (expressed as volumes):

The litter layer in the forest, about 1:30,000.
Raw humus, about 1:10,000–20,000.
Grassland to 12 in., about 1:20,000.

It is difficult to get an impression of the impact of the meiofauna owing to the scarcity of figures for other animal groups. As already mentioned, the earthworm makes a very large contribution to the total biomass under mull conditions. Bornebusch's population for the beech mull numbered 716,000 per acre and weighed 473 lb. (53 g. per sq. m.). His maximum population was 1,450,000 weighing 1,590 lb. (200 g. per sq. m.), and he pointed out that this population was equivalent to the weight of livestock per acre carried by a first-class Danish pasture. This compares very favourably with Evans's (1948) maximum population obtained in a 300-year-old pasture at Rothamsted, the corresponding figures being 647,000 and 1,232 lb. per acre (138 g. per sq. m.). Nielsen (1949) suggests an average population of free-living nematodes of 10,000,000 per sq. m. weighing 12 g. In addition he provides figures (Table 14) for a site very similar to Bornebusch's spruce mor (locality No. 8), where he obtained 1,700,000 nematodes per sq. m. weighing 4·5 g., equivalent to 0·09 c.mm. per c.c. (taking sp. gr. as 1; actual value 1·02 according to Nielsen).

One may ask how does the soil biomass compare with other communities? It hardly compares with Park's (1938) 32 g. of flour supporting 89 live flour beetles (*Tribolium confusum* Duval), or nearly 3 per gramme. Mare (1941–3) carried out a quantitative investigation of the bottom fauna of the sea, the samples being taken from a 45-m. deep marine mud sediment near Plymouth. The total macro- and meio-benthos numbered 149,000 per sq. m. (maximum depth sampled 10 cm.) and weighed 109 g. Her meiobenthos (organisms separated by 0·1–1 mm. sieves) might correspond approximately to the Acari and Collembola of terrestrial soil habitats, for although the upper size limit of her group is lower, the mean weight per individual (0·0078 mg.) compares favourably with the values quoted in Table 5. The biomass of meiofauna (to depth of 2·5 cm.) was 0·046 mg. per c.c., which is equivalent to 1 : 22,000 (sp. gr. taken as 1). Although the total biomass of macro- and meio-benthos is greater than the forest habitats already discussed, it is probably less than good grassland, whilst the meiobenthos is rather less than the equivalent of mor raw humus.

Finally let us contrast the attributes of mull and mor from the point of view of population numbers. We have, on the one hand, larger organisms, greater biomass, a greater depth of substrate inhabited and therefore a more equable distribution of the primary environmental factors living space, oxygen, water, and food, and the results of which are a constant interchange of materials from surface to interior and vice versa. Nutrients are extracted by deep-rooting plants (especially grasses) and finally deposited on the surface when the reverse cycle of transport and oxidation is undertaken by soil plants and animals. Earthworms play a vital role in the second cycle bringing organic and mineral matter into intimate contact, a mixing process achieved in their gut, and finally depositing the fruits of their labour, often at some distance from their source. Plant roots also have an important translocatory function, somewhat similar to earthworms. As they die they are attacked and consumed by the fauna, and the resulting channels provide arteries for communication and additional living space. Here is a biological system with a positive and conspicuous development of the attributes necessary for soil life; each biological unit by its labour and efforts is weaving a pattern which is in sympathy with the requirements of its neighbour, and in turn is seized and elaborated by the next before passing to a further member of the community.

Mor, on the other hand, is an impoverished system with smaller organisms and smaller biomass. The fauna have little mechanical influence on their medium. They live in an environment of organic remains, a separate discrete layer, and are cut off from the mineral soil beneath. Plant roots to a large extent inhabit and exploit the same environment, and actively compete for the smaller amounts of nutrients. Roots are the sole mechanism for extraction of nutrients from the deeper layers, and survival often depends upon their success in this process. This population compression creates a vicious spiral which embraces in a stranglehold grip the living material of the mor, and leads to a contracting milieu, an ever-narrowing zone of life.

These descriptions of mull and mor may stress the co-operation of the one and the competition of the other. But without competition, constructive survival is impossible, and the competition of a fertile mull is undoubtedly intense, probably more intense than the somewhat lower geared mor biome. Rather is the mull expanding its universe whilst the mor is ever contracting and tying up energy which, if allowed to span its full course, will require cataclysmic conditions to secure its release and re-utilization.

Qualitative Aspects of the Soil Faunal Population

Various classifications have been suggested for the organisms inhabiting soil, depending upon the particular attributes uppermost in the mind of the classifier. They can be considered from the point of view of site of habitation: surface inhabitants, passive dwellers such as pupating insects, accidental visitors, &c. Our primary concern is the active soil population and its function in the life of the soil, and the most suitable classification for this purpose is one describing the food habits of the individuals in so far as they influence the chemical and physical properties of their medium. The primary functions of these creatures might be regarded as follows (Jacot, 1940):

1. Reducers of litter and organic material.
2. Mixers of organic residues and mineral soil.
3. Channellers of the soil.

Some organisms, earthworms for example, may perform all three tasks, but for the smaller creatures only the first two apply. For these there are at least eight food categories (in part after Jacot, 1936):

1. Phytophagous (living plants).
2. Saprophagous (dead vegetation).
3. Fungivorous (fungi).
4. Algivorous (algae).
5. Bacteriophagous (bacteria).
6. Predaceous (living animals).
7. Coprophagous (animal excrement).
8. Necrophagous (dead animal matter).

The soil Acari and Collembola, with representatives in all eight divisions, are amongst the most widely distributed animal groups, and occur in practically all situations where vegetation is growing, where they will be found living amongst the decaying material provided by plants. Thus they occur in a great diversity of habitats ranging from the tropical rain forests of Panama (Williams, 1941) and the deserts of Egypt and the Sudan (Trägårdh, 1905, 1929), through the temperate zone to the Arctic tundra of Greenland and northern Canada (Hammer, 1944, 1952). They are present at high altitudes in the mountains of Austria (Franz, 1943, 1944), and are early invaders of embryo soils (Kühnelt, 1942, 1950) where they join with minute representatives of the plant kingdom in the long process of development which gradually builds up the soil surface.

In common with many soil creatures they tend to shun light and display marked thigmotactic responses. If, for example, crumpled filter-paper is placed in a culture, many species of Acari will invade the filter-paper owing to their response to tactile stimuli. In the dark pores

and interstices of the soil one can visualize these creatures browsing on fungi or hunting for prey, their bodies in frequent contact with soil surfaces as they wriggle and squeeze through the labyrinth of arteries and caverns which form their environment. Their atmosphere is usually saturated with water, and this factor more than any other controls their distribution in the surface soil layers. As would be expected, many species show special adaptations to assist them in their life in this specialized substrate. There is frequently a dorso-ventral flattening of the body, reduced leg size, and other characters which wed them to their habitat. Changes are particularly noticeable as one passes from the surface to deeper layers. Surface-dwelling Collembola, for example, have eyes, a pigmented integument, and a well-developed posterior springing organ (hence springtail). The springtail inhabitants of the deeper layers are sluggish, white creatures without eyes, and the spring may be reduced, or completely absent.

Both in respect of number of individuals and number of species, Acari or mites are the most abundant soil arthropods. They are present in practically all soils, and these representatives of the Arachnida may be found in situations ranging from sea water to the surface of stone monuments, and in dry-land habitats from the littoral zone to embryo soils at high altitudes. The adults are eight-legged creatures with a size range of 0·1 mm. or less up to about 2 mm. Mites may possess eyes, but they are frequently absent, and are replaced by elaborate sensory setae performing the same function. Many species respire by means of tracheae which ramify through the body and lead to spiracles on the surface; some, however, rely on the diffusion of gases through their integument. As would be expected from their occurrence in many different habitats, the variety of form and adaptation to specialized living conditions is very great indeed. There are many parasitic species and others have commensal relations with insects to varying degrees.

The typical life-cycle consists of the following stages: egg → six-legged larva → 2–3 nymphal stages (eight-legged and usually active creatures) → adult. Parthenogenetic reproduction may be quite common (Grandjean, 1948). In many considerable external changes take place during the passage from larva to adult, and frequently the immature form is so unlike its parent that it has been erroneously described as a separate species. Some members appear to have an unusually long life-cycle for such small creatures. Some of the Oribatei, for example, may have a yearly cycle, and the writer has maintained adults of this group for a year in culture at room temperature. Little is known of the biology of soil mites, partly due to the difficulty of culturing creatures with such exacting humidity requirements, especially in the young stages. Principal predators are small spiders, beetles, and predatory mites.

The Acari may be subdivided into the following suborders: Cryptostigmata, Prostigmata, and Mesostigmata. The Cryptostigmata can be divided into two well-defined groups, the Acaridiae and Oribatei. The former are soft-bodied, white creatures and include the cheese mites which are important pests of stored products. They occur to some extent in soils and are interesting because of their ability to live under

conditions of low oxygen and/or high carbon dioxide concentrations. The Oribatei are probably the commonest soil- and litter-dwelling mites, and are characterized by their sluggish gait, dark pigmentation, and strong armour, hence the name beetle mite. One group, the Ptyctima (Plate I A), possesses the faculty of being able to fold up into a ball if disturbed, and in this condition resembles a plant seed. At one time the Oribatei were regarded primarily as inhabitants of moss and lichens, but they have since been found in many situations, though they appear to feed to some extent on moss (Cleat, 1952). Choice of food is fairly wide, though individual species may show marked specificity. The principal food sources are probably decaying vegetable material, fungal hyphae, and spores. Their mouth parts are of the biting type, and in the case of litter-feeding species the leaf material they ingest is broken up into very small particles.

The Prostigmata are a more heterogeneous assortment of mites, and taxonomically the least worked of the order. They are usually small (some of the smallest species belong to this group), thinly chitinized, brightly coloured, and frequently possess eyes. Their mouth parts are of a piercing and sucking pattern. Little is known of their biology and food habits as they are extremely difficult to culture. It is probable, however, that they have a greater range of food habits than the Oribatei; some are known to be predatory whilst others may feed on fungi and saprophagous material. It has been suggested that they are more typical of warm, dry habitats (Trägårdh, 1929), but this is not at all certain as they occur in large numbers in temperate soils, and low numbers in some surveys may be a reflection of poor extraction technique.

The Mesostigmata (Plate I B) are as a rule, large, brown, well-chitinized mites. They are predominantly predatory, occurring in the surface and subsurface layers of the profile. In keeping with their predatory role, they are usually active creatures with long slender legs and are not markedly negatively phototropic. This group has varied feeding habits, but carnivorous forms predominate, for example feeding on nematodes, enchytraeid worms, and small insect larvae, small worms, and other small decomposing soil animals (Kühnelt, 1950). Some appear to be coprophagous, and others are facultative carrion feeders which attach themselves to dung and carrion beetles and are thus transported from one food source to another. Some of the best indicators of site conditions may belong to this group as there is a great diminution in kinds and numbers under poor conditions. Unfortunately they are at present extremely difficult to identify.

The Collembola (Plate I C), like the Acari, have a remarkable geographical range, and indeed no other insect order has such a general distribution of species throughout the faunal regions of the world. They have been found in a great variety of habitats, including caves and human graves (Folsom, 1902). They are primitive insects of very ancient lineage; fossil remains of an insect resembling a springtail have been found in Lower Devonian rocks in Scotland (Hirst and Maulik, 1926). The earliest known fossils of winged insects occur in the Upper Carboniferous era, which makes the Collembola about one-third older than

the earliest winged insects. They are frequently brightly coloured creatures with a size range of 0·3 mm. to approximately 1 cm., having three pairs of legs and six abdominal segments which distinguish them from other orders of the class Insecta. Eyes are normally present. They have an unusual springing organ attached to the posterior part of the body by means of which they can leap relatively great distances. Respiration is usually cutaneous, though some forms possess tracheae with spiracles. Reproduction takes the form of eggs laid in batches of 8–12 or more, a characteristic which may be partly responsible for the tendency for populations to show an aggregated arrangement. The eggs hatch to nymphs which unlike many insects have an external appearance very similar to the adult, except for their smaller size and absence of pigment. The young springtail moults a number of times before reaching the adult stage, the complete cycle from egg to adult taking about 5–6 weeks (Kühnelt, 1950, quoting unpublished research of Bruschek).

The order may be divided into two groups, the Arthropleona and Symphypleona. The former are characterized by their elongate form and large spring mechanism; most of the litter and soil species belong to this group. The Symphypleona are spherical in shape and include some of the smallest species; they are predominantly surface-dwelling. They are found in large numbers in decaying timber, and Fourman (1938) has suggested that they are capable of attacking completely undecomposed wood.

Collembola are reputed to be somewhat negatively phototropic, but the physical factor of greatest importance in determining distribution is humidity (Agrell, 1941). Although more sensitive than Acari to moisture status they are better able to withstand short periods of flood conditions, and some species can survive for a time in air-filled capillaries where they roll themselves up until the advent of more suitable conditions (Kühnelt, 1950, quoting Wittasek, 1947).

Although the largest numbers are present in the surface layers of the soil, a few species can occur at considerable depths; Handschin (1925), for example, found them occurring at a depth of 6 ft. These subterranean forms show very characteristic adaptations to their environment, adaptations which include absence of spring, eyes, and pigment. Collembola are often found in large numbers on the surface of snow (hence the name snowflea), where they feed on pollen grains (Gisin, 1947). They are especially prevalent in spring, and Kühnelt (1950) suggests that they come to the surface to avoid the melt waters which saturate the soil beneath. Here, perhaps, is an instance demonstrating the importance of the moisture status of their environment, conditions being such that their normal distaste for light is overcome because of their inability to withstand excessive moisture.

Springtails, on occasion, show a remarkable capacity for 'swarming', and enormous aggregations have been recorded in the literature, but the reasons for their occurrence are unknown. Park (1949) described an example where he found large numbers of an *Achorutes* species oozing in a solid mass from abandoned burrows of the ground squirrel, and estimated a density of 4 million for an area of 6 sq. ft. Elton (1927)

mentions an interesting case occurring in Switzerland where railway tracks were so covered with Collembola that the wheels of the engine slipped and could not move forward.

These creatures have not such specialized food habits as mites. They are known to consume decomposing plant material, fungal hyphae and spores, dead flies, fly-casings, other Collembola and their castings, algae, and pollen grains (Kühnelt, 1950). In addition Gisin (1947) has reported the presence of soil particles mixed with organic material in their gut, which suggests a process analogous to the earthworm, whereby they take part on a smaller scale in the important task of mixing mineral and organic detritus. Their principal predators are said to be spiders, beetles, especially Staphylinidae, and predatory mites such as the Gamasides.

TABLE 6

Proportions of Acari and Collembola in various Habitats

(For details of sampling procedure, &c., see Tables 3 and 4)

Author	*Habitat*	*% of total population*			*Ratio Acari: Collembola*
		Acari	*Collembola*	*Others*	
Arthropod fauna only					
Salt, G., *et al.*	Grassland	68·8	20·3	10·9	3·4:1
Macfadyen, A.	Fenland	84·3	15·7	..	5·4:1
Murphy, P. W.	Cultivated heathland	90·5	8·1	1·4	11:1
,,	Natural heathland	95·2	3·8	1·0	25:1
Meio- and Macro-fauna					
Bornebusch, C. H.	Beech mor	50·5	36·8	12·7	1·4:1
Ulrich, A. T.	Beech–oak mull	54·9	40·0	5·1	1·4:1
Bornebusch, C. H.	Beech mull	51·8	19·4	28·8	2·7:1
,,	Spruce mor	69·3	19·3	11·4	3·6:1
Ulrich, A. T.	,,	73·2	20·5	6·3	3·6:1
Van der Drift, J.	Beech mor	80·3	19·5	0·2	4:1
*Forsslund, K. H.	Spruce–pine–birch mor	85·3	14·2	0·5	6:1

* Figures from Table 4 (Forsslund's locality II).

When one comes to consider the interrelationships of the Acari and Collembola, it is difficult to find any obvious pattern in present data. In Table 6 the proportions of these organisms in the surveys already discussed are arranged in an ascending scale of Acari. The latter in all cases outnumber the springtails, though in the early surveys the ratios are close to 1, a result which is undoubtedly due to faulty extraction technique. As mentioned earlier, Trägårdh and Forsslund (1932) suggested that Bornebusch's totals represent only 10 per cent. of the mites and 2 per cent of the springtails; however, examination of the table suggests that in some cases the relative proportions are reasonable whereas in others the Acari have been underestimated to a greater extent

than the Collembola. The figures of Table 6 show a tendency for proportionately greater numbers of mites under mor conditions and in less fertile habitats. On the other hand, although Collembola-dominant populations have not been recorded in this country, Austrian figures (Riha, 1944) indicate a preponderance of Collembola in certain soils (terra fusca: brown limestone clays). In explanation, Kühnelt (1950) suggests that there is a close quantitative relationship between fungi and Acari (especially Oribatei), and in habitats suitable to the latter certain species of fungi are kept in check by these mites. In soils with less favourable environmental conditions for Acari, Collembola replace them and become messmates of the dominating fungal species.

If one seeks the underlying causes responsible for these variations, little assistance may be gained from the literature, where opinions are conflicting. Frenzel (1936), for example, found Collembola dominant in moist meadows (there were exceptions) and Acari in dry meadows. He suggested that space and not competition for food was the primary factor; he also thought that biotic factors, not clearly discernible, were at play. Agrell (1941), although not minimizing competition for space, considered soil humidity the most important criterion deciding dominance. He found large numbers of Oribatei in dry situations, but as his study was directed towards the Collembola, his conclusions though suggestive cannot be considered conclusive. Hammer (1944), in her Greenland study, found springtails dominant in certain habitats, and this fact did not appear to be wholly dependent on moisture. However, as she only dealt with the oribatid group of mites, it would be unwise to place too much weight on these implications. Kühnelt (1950) considers that there is little direct competition between Acari and Collembola for space or food, and suggests fungal competition, and this biotic factor might well be an important influence, as Frenzel had tentatively suggested in his earlier study.

A fact that appears to have escaped attention when considering the alternation of dominance between Acari and Collembola in different situations is the periodic and often violent fluctuations in environmental factors occurring in any one habitat, and in the ability of a particular organism to withstand the impact of these variations may lie the clue to the dominance of one or other group. Whether Acari are more resistant than Collembola to adverse conditions is not at all certain, though the indication that the former (especially Oribatei) are more easily cultured is a point in their favour. On the other hand, the more rapid reproduction of the Collembola and their apparent ability to build up numbers after deleterious conditions is a valuable asset. It may be that the greater generative capacity of the Collembola is counterbalanced by a greater mortality in adverse conditions. However, it must be borne in mind that Collembola show a greater tendency to aggregate, and as this phenomenon has not been examined in any detail it is possible that present figures are biased favourably or unfavourably from the point of view of population numbers.

So much for the characteristics and attributes of these two animal groups, but this would be a one-sided picture without a discussion of soil

properties and their effect on these creatures. However, before passing to this subject it might be pertinent to consider briefly the present pedological approach to mull and mor.

The number of firmly established facts about these formations are few. Mor is characteristic of well-drained, acid habitats (pH 3–6·5), especially heathland and coniferous forests. The raw-humus accumulation can be divided into a litter layer on the surface, overlying an F layer where decomposition is taking place but where the external structure of the litter is still evident, and passing to the structureless brown 'humus' of the H layer. In these soils the amount of available calcium is low, nitrates can hardly be detected, and ammonium nitrogen is present in very small quantities. The mull formation typically occurs with mixed or deciduous forests on moderately well-drained soils. The acidity range is normally pH 4·5–8, there are reasonable supplies of calcium, and the amounts of ammonium and nitrate nitrogen are greater than in mor soils.

Müller regarded mull and mor as biological and not purely physico-chemical systems, and considered that the fauna present was an important tool in the formatory process. A few have followed up Müller's findings in the light of present knowledge, but many pedologists have stressed physical and chemical rather than biological mechanisms. Mor has been regarded as a situation where organic matter is accumulating, and there has been much discussion of *rate* versus *type* of decomposition in typical profiles. However, as Romell (1932) has ably demonstrated, the differences in amount of organic matter may not be so very great if they are expressed on a volume rather than weight basis. Indeed there must be some organic-matter accumulation in a mull grassland, otherwise the usual assumption of oxidation of accumulated reserves and their benefit to the succeeding arable crop would not be valid. However, total organic-matter content does not take into account the humus turnover; it does not indicate the rate of humus loss or reduction to small residues. Under forest conditions there is the undoubted fact that litter accumulates in mor so that unless the quantities of litter reaching the surfaces of mull and mor are very different, the rate of decomposition must be slower in the latter, though the difference may not be as striking as the appearance of mor would suggest.

The theory that type rather than rate of decomposition is the important criterion is an attractive proposition when soil organisms are considered. In mor, nitrifying bacteria are absent and biological activity is confined to a small volume of soil, resulting in severe competition between plant roots, fungi, and fauna for the small amounts of such vital nutrients as nitrogen. Thus it is suggested that under the usually acid conditions of mor the main agents in decomposition are fungi, not only free-living species but also mycorrhizal forms associated with plant roots. They achieve a partial breakdown, the resultant products being locked up in living and dead biological organs, e.g. 'the brown hyphae' of Müller. The peculiar behaviour of stored mor samples, when some nitrates and quite a lot of ammonium nitrogen can be detected after storage, is a point in favour of the argument that the mechanism of nitrogen

immobilization is a biological one. In mull there is less acidity, a more equable base status, and bacteria tend to replace fungi. There is a greater volume of soil inhabited by flora and fauna, and nitrogen is not a limiting factor. A further important point is that activity and movement of larger organisms in the profile will provide the micro-fauna and flora with a means of transport so that their chances of contacting suitable substrates are greatly increased. There is also the suggestion (Kühnelt, 1950) that under these conditions soil organisms prevent the development of fungi of a strongly competing type, and this is a plausible hypothesis in situations which might oscillate between mull and mor with small changes in one or two vital factors.

There is evidence that acidity in mor is not merely due to leaching of bases and extreme unsaturation of the humus colloids but to actual production of acids, for example by fungi (Romell, 1935). Further, Romell (1935) has pointed out that if organic acids are formed, their effect upon acidity and hence upon leaching and base saturation must depend very much on nitrogen status. With adequate nitrogen their effect will be small, for under such conditions they form excellent nutrients for many micro-organisms. If type of decomposition is the real criterion—and there is evidence that it is—then, practically speaking, different types of 'humus' are being elaborated in each case by different biological complexes, and an understanding of nitrogen status and mode of utilization may prove the keystone to the problem.

Living-space, oxygen, water, and food are the most vital requirements of the soil faunal population. Amount and kind of soil pore space is of prime importance because it not only determines the nature of the living space but also has a very great effect on the humidity and gaseous conditions of the environment. Kühnelt (1950) suggests that there is a relationship between the average size of the soil interstices and the meiofauna inhabiting them. Thus he states (quoting an unpublished study of Wittasek) that in loose soils with crumb structure large species of Oribatei are found, in contrast with the smaller forms of compact soils such as heavy clay meadow habitats. Individual species of the soil fauna show considerable size variations which may well be correlated with the pore-size distribution of the habitat; this is an aspect which in the writer's knowledge has not been investigated. Kubiëna (1938) has referred to the presence of dwarf species of fungi, and Russell (1950) mentions the occurrence of dwarf algae. Although these are reflections of the general characteristics of the environment, as the same species can grow to greater size where space limitations do not arise, they illustrate adaptive processes very necessary for life in the confined spaces of the soil.

As already stressed, soils with litter and raw-humus covering have their faunal populations concentrated in these layers. On this account it might be suggested that this milieu provides very suitable living space and environmental conditions. Undoubtedly the large pore volume makes it unlikely that living space is a limiting factor. On the other hand, the loosely knit structure of the litter facilitates wide fluctuations in humidity, and therefore reacts unfavourably from the point of view

of its inhabitants. This may be partly responsible for the concentration of population and presumably activity at the junction of the F and H layers (Forsslund, 1944–5; Van der Drift, 1951). However, it is impossible to decide whether mor provides a better physical environment because, with the possible exception of beech mor, this condition is the result of a number of deleterious factors which may override living-space considerations.

TABLE 7

Pore Volumes of Natural and Cultivated Heathland (after Rennie, 1951)

	Horizon depth (in.)	*% total porosity*	*Winter 1949–50*		*Summer 1950*	
			% air	*% water*	*% air*	*% water*
Natural heathland						
Raw humus . .	0–1½	75	9	66	39	36
Brownish-grey bleached horizon . . .	2–7½	52	8	44	26	26
Cultivated heathland						
Inverted bleached layer	3–8	45	10	35	23	22
,, raw humus	8–10	75	32	43	42	33
Undisturbed raw humus	10–12	70	25	45	40	30

Note: Sample site Silpho Moor, Allerston Forest area, Yorkshire, which corresponds approximately to site used for faunal survey of natural heathland quoted in Table 3 and Fig. 1. Cultivated site rather different as the ploughing is much more recent (1947 compared with 1931), and deeper than site used for faunal assessment. In addition the trees had reached canopy in the latter.

Unfortunately pore-volume and size-distribution data of sites which have been investigated for soil fauna are very meagre. Table 7 outlines Rennie's (1951) determinations for natural and cultivated heathland in the Allerston Forest area. The determinations represent winter and summer conditions, but the summer values operate for a very short period. These figures indicate that only 9 per cent. of the volume of raw humus of the natural heathland is available to aerobic organisms, the populations being 9·6 per c.c. of the gross volume and 82·2 per c.c. of air-filled pore. It is also worth noting that though the total pore volume of the mineral soil is only two-thirds of the raw-humus value, the air-filled pore space almost equals the raw humus.

Thamdrup (1939) has ascertained the relative humidity of raw humus of a Danish heathland and has found that a moisture content of 10–20 per cent. (dry matter+water = 100 per cent.) corresponds to a R.H. of 75–90 per cent. He considers that even under very severe drought conditions (moisture content of about 30 per cent.), the R.H. does not fall below about 90 per cent. This evidence corroborates the view that low humidity is rarely a limiting factor in the F and H layers of the heathland; if anything, there is a surfeit of water especially in the more compact H layer. Both Pearsall (1952) and Romell (1935) are strongly opposed to the idea that anaerobic conditions are present in mor. Pearsall states: 'oxidation . . . is a necessary precursor of high acidity', and

points out that in lake muds, where conditions are probably always anaerobic, a pH of less than 5·4 has not been recorded. Pearsall (1952) and Romell (1935) have made redox-potential measurements of mor raw humus and the results indicate strongly aerobic conditions, but it is also true to say that pedologists are not in full agreement as to the interpretation of these results. On the other hand, if one considers the heathland profile one wonders whether aerobic conditions prevail right through the raw humus. Is it not possible that the F layer has an oxygen-rich atmosphere, intensely aerobic conditions, and hence the zone of greatest faunal activity, whilst the more compact H layer lacks oxygen? A statement of Romell's (1935), 'If any kind of mor is characterized by poor aeration, it should be the pronounced greasy type, containing few living hyphae in the heavy and compact H layer', suggests that he does not entirely preclude such a situation.

A possible pointer to the oxygen status of heathland may be obtained by a consideration of the vertical distribution of a new species of *Schwiebia*. A full account of the taxonomy and ecology of this mite in collaboration with Dr. A. M. Hughes is being published elsewhere. There is little known of the biology of the genus, but other members of the Acaridiae, to which it belongs, can live under conditions of low oxygen and/or high carbon dioxide concentrations. Hughes (1943), from laboratory experiments, has demonstrated the high resistance of the cheese mite, *Tyroglyphus farinae* L., to carbon dioxide accumulation and lack of oxygen. Examination of the vertical distribution of the *Schwiebia* sp. (Fig. 1) shows a peak just below the main faunal concentration in the raw humus, which decreases to zero at the base of this horizon. A small number occur in the upper portion of the A_2 horizon, and there is a further concentration in the organic matter just above the pan. In this particular profile it is the only mite occurring in numbers below 1½ in.; the other organisms present are subterranean Collembola, and Kühnelt (1950) suggests that these species can live in conditions of low oxygen. Whilst the writer, in view of the previous qualification, would not wish to draw too much from this distribution pattern, there is a suggestion that excess water and lack of aeration may be limiting factors, and this rather sluggish species, perhaps because of competition or predatory enemies, is perforce driven to a part of the profile inhabited by few other mites.

Cultivation is an important artificial process performing a task under arable conditions, which under less intensive forms of husbandry is the function of the fauna. It is generally believed that soil disturbance is deleterious to the larger organisms. However, there is one important instance where cultivation or rather disturbance appears to have an activating effect. Romell (1935) discusses at length the beneficial effect on mor of various forestry operations such as thinning, covering with green slash, surface disturbance, &c., but as he points out, the reasons why activation takes place are not clearly understood. The right-hand diagram in Fig. 1 illustrates the vertical distribution in a profile which has been cultivated and planted with trees (trees about 20 years old and nearing canopy). This cultivation is of a rather special type and is not

equivalent to a simple surface disturbance. A furrow is ploughed out, one for each row of trees, the furrow being turned on to the undisturbed surface and the trees planted on the side of the ridge so formed. The result is that the two raw-humus horizons are brought together to form a 'sandwich', and the distribution illustrated is a vertical section across the centre of one of these ridges, the maximum depth from top of ridge to old surface being about $6\frac{1}{2}$ in. (excluding litter). Examination of the sandwich in this profile reveals a large number of tree roots and a zone of crumbling raw humus, coinciding with the junction of the two raw-humus horizons, and which appears to have undergone further decomposition; this zone may resemble Müller's 'insect mull'. The population of the sandwich, 53 per cent. of the whole (3·6 per c.c.), is quantitatively and qualitatively different to the undisturbed heathland. There is a more even distribution of fauna through the raw humus, and the air and water percentages (Table 7) suggest that more equable environmental conditions prevail in the cultivated profile.

Before passing to the next section where food habits of the fauna will be discussed, let us briefly consider soil acidity and its effect on soil organisms. pH, partly because of its ready measurement, is often used in attempts to correlate soil characteristics with fauna. Amongst the larger creatures its effect on earthworms has received most attention. The general consensus of opinion (Bornebusch, 1930; Stöckli, 1928) is that a value of $< 4{\cdot}5$ is inimical to earthworms, though it would be unwise to regard this as a sharp boundary, and some earthworms, e.g. *Lumbricus rubellus* Hoff., are quite tolerant of relatively acid conditions. Individual species may have broad tolerance ranges, but there are not sufficient data to provide even approximate limits for each species.

For the other soil organisms there is scarcely any precise information, though Acari and Collembola can exist in very acid conditions, as shown by the heathland population, where the pH may be as low as 3 in the surface layers. Broadly speaking, very acid forest soils have large numbers of small creatures and a small biomass, whilst the most obvious characteristics of less acid soils are the greater biomass and faunistically richer population. In fact it may well be that soil faunas bear much the same relation as many plant species to pH, there being calcicole and calcifuge types and a middle group which is largely indifferent. However, it would be dangerous to regard this a result of acidity *per se*; rather is pH a convenient portmanteau measurement where equal values in two sites may be the result of interaction of different factors in each case.

The Role of the Fauna in the Life of the Soil

With one or two exceptions, knowledge of the habits of soil fauna and their physical and biochemical influence on their medium is very meagre. Very little research has developed beyond the population-study stage, but such facts as the large populations present in the litter and F layers, their apparently saprophagous and fungal feeding-habits, and the frequently low bacterial populations of forest sites point to the need of investigation of the role of these organisms as a link in the biochemical

chain whereby organic material is broken down and its constituents released for re-utilization. Their role as a link in the chain of organic-matter oxidation must be of great importance (Kühnelt, 1948). It is quite clear that the presence of a large number of saprophagous creatures must affect the nature of the process, and their occurrence in great numbers under acid conditions in association with fungi, and to the detriment of the bacteria, must be of concern to all who study the breakdown of organic material under these conditions. This statement might suggest that the fauna of acid soils owe their presence to certain primary factors which exercise an overriding influence and that they can have no beneficial effect on their medium. Their study therefore would be of value only as a means of ascertaining the nature of the primary factors resulting in their presence, in other words a negative approach. A refutation of this argument is clearly seen when the breakdown mechanism of cool, well-aerated manure and compost heaps is considered. Franz (1950*a*) has shown that a fauna qualitatively very different to the soil population is present during the initial decomposition process, and he considers that these organisms are responsible for an appreciable fraction of the decomposition taking place. As this process continues there is a gradual change in the nature of the specialized fauna until, when the end-point is reached, the population closely resembles that of good, permanent pasture. This dynamic cycle indicates the changes that might easily be effected by cultural operations and that under certain conditions the state of the complex is one of pin-point balance, and alteration of certain factors might result in violent quantitative and qualitative changes before a fresh and relatively stable population is established. An additional point of interest arising out of this investigation is the fact that previous emphasis on micro-flora and fauna provides a very incomplete picture of the breakdown processes. Therefore the integration of studies of soil organisms under extreme conditions is an obvious approach to the discovery of the primary factors responsible for the nature of the soil meiofauna and ultimately should result in an elucidation of the secondary factors arising from their presence.

The direct, mechanical effect of the meiofauna on their environment is probably small. They are, to a degree, bounded by the larger soil and litter interstices and their movement almost entirely depends on the presence of channels and pores formed by other agencies. Indirectly, however, they may increase aeration and drainage in so far as they eat out decayed roots and thus leave manured channels in the soil (Ghilarov, 1947; Rogers, 1939), an effect perhaps of greater importance under grassland conditions.

Of the mites and springtails, the most important members of the soil meiofauna, it is probable that the majority are saprophagous and fungal feeders. Forsslund (1938–9) examined the gut contents of some oribatid mites and found fungus mycelia present. Others are known to feed on decaying leaves of plants, and Jacot (1939) recorded the presence of nymphs of the Phthiracaridae burrowing within conifer needles where they apparently spend a considerable portion of their early life. The writer (1952) has observed this phenomenon in laboratory cultures.

The fact that litter-feeding species are of importance in determining to some degree the end-point of the decomposition cycle renders experiments to ascertain the palatability of litter of different tree species a valuable study. Various investigators have carried out experiments of this nature in the laboratory with earthworms (Lindqvist, 1941; Franz and Leitenberger, 1948; Franz, 1950*b*), millepedes (Lyford, 1943; Franz *et al.*, 1948), and mites (Noordam and van der Vaart-de Vlieger, 1943; Spencer, 1951). Spencer, working under the writer's direction, found that litter-feeding mite species, when provided with Ash (*Fraxinus excelsior* L.), Birch (*Betula alba* L.), Scots pine (*Pinus sylvestris* L.), and Douglas fir (*Pseudotsuga Douglasii* Carr.), showed a marked preference for broadleaf as opposed to conifer litter, and ash to birch. These preferences have been confirmed by further experiments carried out by the writer (1952) (Plate II). The litters chosen represent broadleaf and conifer species which have reputations for rapid and slow decomposition respectively. Wittich (1943) has shown that the C/N ratio of tree litter is negatively correlated with rate (or type?) of decomposition (see Table 8). Lyford's (1943) feeding experiments with the millepede, *Diploiulus* (*Cylindroiulus*) *londonensis* var. *caeruleocinctus* (Wood), demonstrated a positive relationship between palatability and calcium content of the litter. Unfortunately he did not determine C/N values, but there is an indication that they are negatively correlated with calcium content. In addition Wilson and Staker (1932) found a very definite correlation between the C/N ratios of some New York peats and their calcium contents. Bearing in mind that calcium is essential for the metabolism of the earthworm, there are indications that the calcium content of the litter source may have an important influence on the faunal and floral population, and on the composition of the latter will depend the nature of the humus formation. Further investigations of these attributes in relation to litter-feeding fauna should provide valuable information.

TABLE 8

Carbon: Nitrogen Ratios of Tree Litters after Wittich (1943)

Robinia sp.	14:1	Beech (*Fagus sylvatica* L.)	51:1
Ash (*Fraxinus excelsior* L.)	21:1	Sycamore (*Acer* sp.)	52:1
Hornbeam (*Carpinus* sp.)	23:1	Red Oak (*Quercus rubra* L.)	53:1
Lime (*Tilia* sp.)	37:1	Pine (*Pinus* sp.)	66:1
Oak (*Quercus* sp.)	47:1	Douglas fir (*Pseudotsuga Douglasii* Carr.)	77:1
Spruce (*Picea* sp.)	48:1		
Birch (*Betula* sp.)	50:1	Larch (*Larix* sp.)	113:1

It is probable that physical properties of the litter also have an important bearing on the breakdown process. In culture experiments the writer has observed that the moisture content of the food material is of great importance, and oribatid mites, for example, do not appear to feed on litter unless it is completely saturated. Kühnelt (1950) further points out that there is very little activity in the autumn in freshly fallen litter until it has become thoroughly moistened; however, there is evidence that litter-feeding species will not consume freshly fallen leaves

(Franz and Leitenberger, 1948) for reasons other than lack of moisture. There is no information concerning the length of time leaves, e.g. xerophytic types, will resist the penetration of water, although Spencer's data illustrate considerable differences in moisture uptake of litter species when small pieces of leaves and needles are kept in a water-saturated atmosphere for 10 days, and this may be one reason why certain litters are unpalatable to the fauna.

Apart from the microcosm of litter-feeding fauna and flora, insects feed on the living leaves of the trees of the forest and thereby short-circuit the normal cycle, their excrement providing appreciable amounts of nutrients and sites for further decomposition (Fenton, 1947). Anyone who has walked in an oak forest on a summer's day and heard the gentle patter of falling frass can appreciate the activities of these creatures; and unless the trees are incapacitated by their phytophagous guests, this rain of faeces may make a significant contribution to the forest community.

The biochemical role of the soil fauna is at present extremely obscure. It is generally believed that the majority of the meiofauna cannot digest celluloses, hemicelluloses, or lignins. The fungi, on the other hand, can oxidize these substances, and soil organisms, in turn, may feed on the protoplasm of some fungal species. Their excrement, in its turn, provides a milieu for further decomposition by fungi, coprogenous organisms, &c. Some soil creatures will not feed on freshly fallen leaves, which lends weight to the argument that fungi or other agents perform a preliminary 'softening-up' process before the fauna take over. In this way the soil organic matter may pass through many plants and animals before the end product is reached. Much of this is mere conjecture and further study may indicate the presence of a more comprehensive digestive equipment. An example is Tracey's (1951) discovery of the presence of the enzymes cellulase and chitinase in earthworms. In addition some creatures may be able to degrade these substances by means of the microbial population of their gut. Very little is known of the internal flora and fauna of arthropods, but there are some records, for example the presence of cellulose-destroying bacteria in the gut of the chafer beetle, *Potosia cuprea* (Fabricius) (Werner, 1926), and symbiotic intestinal bacteria in the larvae of the dipterous insect, *Amasia holosericea* Meig. (= *Penthetria holosericea* Meig.) (Kühnelt, 1950). These are pointers to the elaborate symbiotic equipment that may be available to many of these creatures.

The excrement of soil invertebrates will provide an important substrate for further decomposition, and much of the soil organic matter may be present in this form under certain conditions (Kubiëna, 1943). Spencer (1951) has examined microscopically the faecal pellets of the mite, *Steganacarus magnus* (Nic.) (*Hoploderma magnum* (Nic.)). These averaged approximately $145 \times 125\,\mu$ in size, and when crushed were found to contain numerous leaf particles about $5 \times 3\,\mu$. Very few fungal hyphae were observed. This indicates that, apart from any chemical transformations, the role played by these mites in the comminution of decaying leaf tissue is of a high order.

So far we have stressed the synergistic relationships of the biological units responsible for the decomposition cycle, but there are also violent competition and antagonisms, and the latter particularly may have a decisive bearing on the ultimate product. Kühnelt (1950) has suggested that fungi can play an important part in deciding the dominance of Acari or Collembola in particular habitats. The exact mechanism is not understood, but it is not unreasonable to suppose that a process analogous to the production of antibiotic substances may be involved, and there is evidence for this suggestion amongst other groups of soil life. Certain fly larvae, for example, produce substances which prevent the development of bacteria in their vicinity (Kühnelt, 1950). Again, some enchytraeid worms secrete substances which have a harmful effect on nematodes (Jegen, 1920). The nature of the secretions of plants, animals, and fungi and substances leached from litter and other decaying materials and their effect on life in the soil is a vast field which should amply repay investigation.

The 'Activity' of Soil Organisms

At present it is impossible to define precisely the value of the soil fauna owing to lack of information concerning their 'activity', but it is clear that, apart from mechanical functions, their role in the mineralization of plant residues is not inconsiderable. The diversity of fauna in a good mull soil may be one of its greatest assets because the humification process flows through a wide variety of organisms with varying metabolisms and offers better opportunities for degradation of intractable materials. Nielsen (1949), whilst recognizing their part in humification, makes the interesting suggestion that the soil fauna's most important function is to act as a reserve or buffer of easily available and rapidly circulating substances. From this point of view the qualitatively rich fauna of mull would further enrich their habitat.

The quantitative estimation of the importance of the soil population is the obvious goal of the investigator. The biomass values already discussed tell us nothing about the 'activity' of the population, and indeed they can be misleading, for Bornebusch (1930) has shown in his respiration experiments that oxygen intake, and therefore food consumption per unit body weight, is less for large than for small soil animals. A number of investigators (Soudek, 1928; Bornebusch, 1930; Ulrich, 1933; Nielsen, 1949) have attempted to measure the importance of the different types of organisms in the soil, but their results for the most part are unsatisfactory owing to the experimental difficulties involved. The methods used by these workers fall into two categories. Bornebusch, for example, using an indirect method, estimated the oxygen consumption of representative members, and with these basic figures calculated the total consumption per unit area for his habitats. Table 9 gives the oxygen consumptions of the fauna in Bornebusch's localities; they are the same as those already discussed in the quantitative section. These figures may have a significant relative value, but the absolute values are unsatisfactory owing to the many unreliable suppositions, and his underestimation of the numbers of organisms. In the beech

TABLE 9

Numbers, Biomass, and Oxygen Consumption of Meiofauna and Macrofauna in Danish Forest Soils (Bornebusch, 1930)

(For details of sampling procedure, &c., see Table 4)

Habitat	*Numbers per sq.m. (Thousands)*	*Biomass per sq.m. (g.)*	*Oxygen consumption per hour at 13° C. (mg.)*
Beech mull . .	6·2	70·77	19·73
Beech mor . .	19·4	16·57	11·97
Spruce mor . .	11·9	9·84	7·09

mull earthworms constitute 75 per cent. of the biomass and 55 per cent. of the total respired; in beech mor the figures are respectively 7 and 3·5 per cent. On the other hand, Acari and Collembola in beech mor represent 5·7 per cent. of the biomass and 27·1 per cent. of the respiration total, the equivalent figures for spruce mor being 6·0 and 25·4 per cent. These results quite obviously underline the statement already made concerning size of organism and its 'activity'. It might be interesting to hazard a guess of the volume of oxygen available to soil fauna in the undisturbed heathland as pore volumes have been ascertained for this habitat (Rennie, 1951; see p. 163 and Table 7). If one assumes that the soil atmosphere is completely saturated with water vapour and has the gaseous composition of air, the amount of oxygen available in the raw humus of the heathland (omitting litter layer) at normal pressure and a temperature of 13° C. is 0·565 g. per sq. m. On the basis of Bornebusch's value for spruce mor, this volume would provide sufficient oxygen for the needs of the soil meio- and macro-fauna of the F and H layers for a period of 80 hours (temperature 13° C.).

A second method of approach is to ascertain the food consumption of the fauna, and a number of investigators have attempted to do this with earthworms (Lindqvist, 1941), snails (Lindqvist, 1942), millepedes (Lyford, 1943; Franz and Leitenberger, 1948; Van der Drift, 1951), and mites (Noordam and van der Vaart-de Vlieger, 1943; Spencer, 1951). Spencer's attempts to obtain a quantitative estimate of the litter consumed were somewhat inconclusive for a variety of reasons. However, a consumption of 0·35 mg. per mite (*Steganacarus magnus* (Nic.)) per 100 days was obtained when the mites were cultured on ash litter at 4–5° C. Of this total about 50 per cent. was excreted. The size of these organisms, too large for the techniques of the microbiologist and yet too small for the macro-methods normally employed with insects, demands a reorientation of methods before progress can be made. Macfadyen's (1948) interesting theoretical discussion of the 'activity' of organisms offers a solution providing the experimental difficulties can be overcome.

The Soil Fauna in Relation to Forestry Practice

The fate of plant residues after passage through the gut of soil organisms and their partial or complete humification by the fauna will depend primarily on the nature of the biological complex. The outward

expression of this 'end-point' is the formation of mull or mor or the many intermediates lying between these extremes. The forester, often perforce driven to marginal areas, must consider this humus condition of great importance, though its study is not entirely his prerogative, as is remarkably well shown in the more acid Rothamsted Grass Plots where the accumulation of partially decayed grass litter indicates an incipient mor (Russell, 1950).

Many suggestions have been made in endeavours to ameliorate mor conditions. It should be stressed that mor in itself need not be deleterious as many conifers grow naturally and produce good timber under these conditions. Romell (1935) has pointed out that mull may be unfavourable to timber-producing conifers. Thus some of the famous mixed pine and spruce plantations at Jönåker in Sweden (Schotte, 1921) are growing on mor soils. Mull conditions may give rise to such effects as poor form and heavy limbs in Scots pine (*Pinus sylvestris* L.), heart rot and apparently reproductive difficulties in Norway spruce (*Picea excelsa* Link.) (Lindqvist, 1932). However, a change from the extreme condition is advantageous in situations (e.g. the Danish heathlands) where a small change will produce either end-point. In situations such as this, and with intensive forestry practice, it is clear that a more equable distribution of organic matter in the profile can play an important part in the quest for greater productivity. The forester in his choice of tree species has an important tool at his disposal for the amelioration of site conditions, and here it might be pertinent to consider briefly tree species and its impact on mull and mor. Usually conifers and broadleaf trees are regarded as the respective plant representatives of these conditions, but this division whilst broadly true is by no means as clear cut as would appear at first sight, as witness beech (*Fagus sylvatica* L.) associated with mull and mor in Europe, and Red Oak (*Quercus borealis* Michx. f. var. *maxima* Ashe) with mor in U.S.A. Amongst the conifers, Red and White Cedar (*Juniperus virginiana* L. and *Thuja occidentalis* L.) are associated with mull conditions in America.

The precise mechanisms involved in the relation between tree species and humus formation are not clear. Chandler (1939) has demonstrated a correlation between the calcium content of mature leaves of tree species and their reputations as mull or mor formers, and there are many obvious reasons for the importance of adequate calcium supplies. Chandler has suggested that where soil calcium is becoming a limiting factor, the function of a tree species of the soil-improving type may be to make the most of these supplies by maintaining adequate quantities of calcium in the litter layer. As already mentioned, there is some evidence that the calcium content of litter is correlated with its palatability which in turn may be correlated with its C/N ratio. Perhaps also correlated with calcium, though the relation may be indirect, is the effect of tree species on the acidity of the site. Unpublished data of Ovington, cited by Pearsall (1952), indicate that tree species can have a considerable effect on pH even over a short period. Pearsall, quoting these data, mentions that the surface layers of the soil, beneath 20-year-old trees growing on a site which was originally mixed woodland, had a pH of

5·4 for *Quercus rubra* L. and 4·6 for *Picea omorika* Bolle as compared with the original value of 5·1. The effect of a so-called soil-improving tree species can be strikingly seen in some of the experimental plots in the Allerston Forest area (Yorkshire), which is very acid heathland. The writer (1951) has found earthworms (*Lumbricus rubellus* Hoff.) present in young birch plantations, and Dimbleby (1950, 1952) has shown how mull conditions tend to develop under birch even in quite young stands.

Another practice which may assist the forester in his search for greater productivity is the use of tree mixtures. It is well known that the mixing of a species whose litter is not readily humified with more palatable types results in an amelioration of the overall humus conditions, though the processes involved are little understood (Wittich, 1933). Field observations made by Spencer (1951) in conjunction with his laboratory experiments revealed very few *Steganacarus* mites under ash and birch, which suggests the hypothesis that some of these organisms may play a part in the more rapid litter decomposition which frequently occurs in mixed broadleaf and conifer stands. The accumulation of conifer needles may provide suitable environmental conditions, whilst the broadleaf litter provides palatable food material for the maintenance of litter-feeding populations of soil Acari at a high level (Murphy, 1952). Naturally the forester must consider the economics of his crop, but under certain conditions there seems to be a case for planting tree mixtures which in addition have other recommendations, and the use of pioneer species to condition a site and prepare it for greater productivity (Dimbleby, 1950). These are important aspects of forestry research that should amply repay further study.

Conclusion

In the writer's opinion it is not possible to apply directly the present modicum of knowledge of the soil fauna in devising practical measures to assist in forestry operations, one of the obvious reasons being the lack of knowledge of the habits of these creatures and, worse still, the paucity of information concerning the magnitude and nature of populations occurring under different conditions. Although the immediate application of measures in this sphere is not feasible, there are obvious indications of its potentialities, especially in the use of these creatures as indicators of particular conditions, in the short-term view of particular edaphic conditions, and the longer-term possibility of using soil populations together with other criteria as indices of the attributes of forest sites (Murphy, 1949, 1952).

Franz (1949), in Austria, attempted an assessment of soil characteristics of grassland by quantitative zoological methods and found that an analysis of the soil population in many cases showed close agreement with indices applied by the Austrian Soil Mapping Bureau and obtained by the more usual methods of soil assessment. This use of the soil faunal population as a site index is an attempt to extend to soil organisms the ecological concept of vegetation as indicative of certain conditions (e.g. a measure of fertility level) by utilizing the characteristics of the faunal population either in association with or parallel to the vegetation

pattern of a site. It is well known that some soil organisms are ubiquitous or at least occur in wide geographical areas and under varied edaphic conditions; on the other hand, certain species are closely associated with particular habitats. Such an indicator species or population complex is an outward expression of the interaction of many factors and could be used as a qualitative and quantitative measure of the attributes of a particular site. An analysis of this type may integrate vegetation and site in a manner which is not possible when the former alone is taken as criterion. Apart from an overall assessment, soil fauna may prove good indicators of specific factors; this aspect might be extremely useful in ascertaining certain soil properties, e.g. aeration (Murphy, 1949, 1952), which are otherwise difficult to measure. In conclusion it must be stressed that much remains to be done before this branch of soil biology can even begin to be of benefit to forestry. In the words of Franz (1950*b*): 'There are few branches of knowledge where each barrier must be surmounted by such hard and detailed work.'

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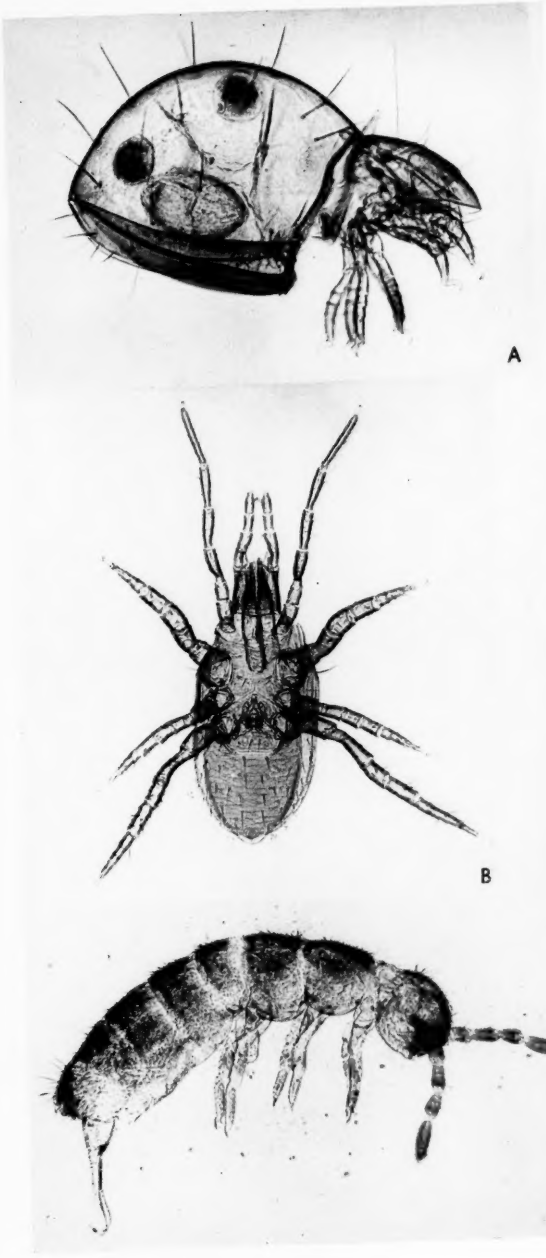

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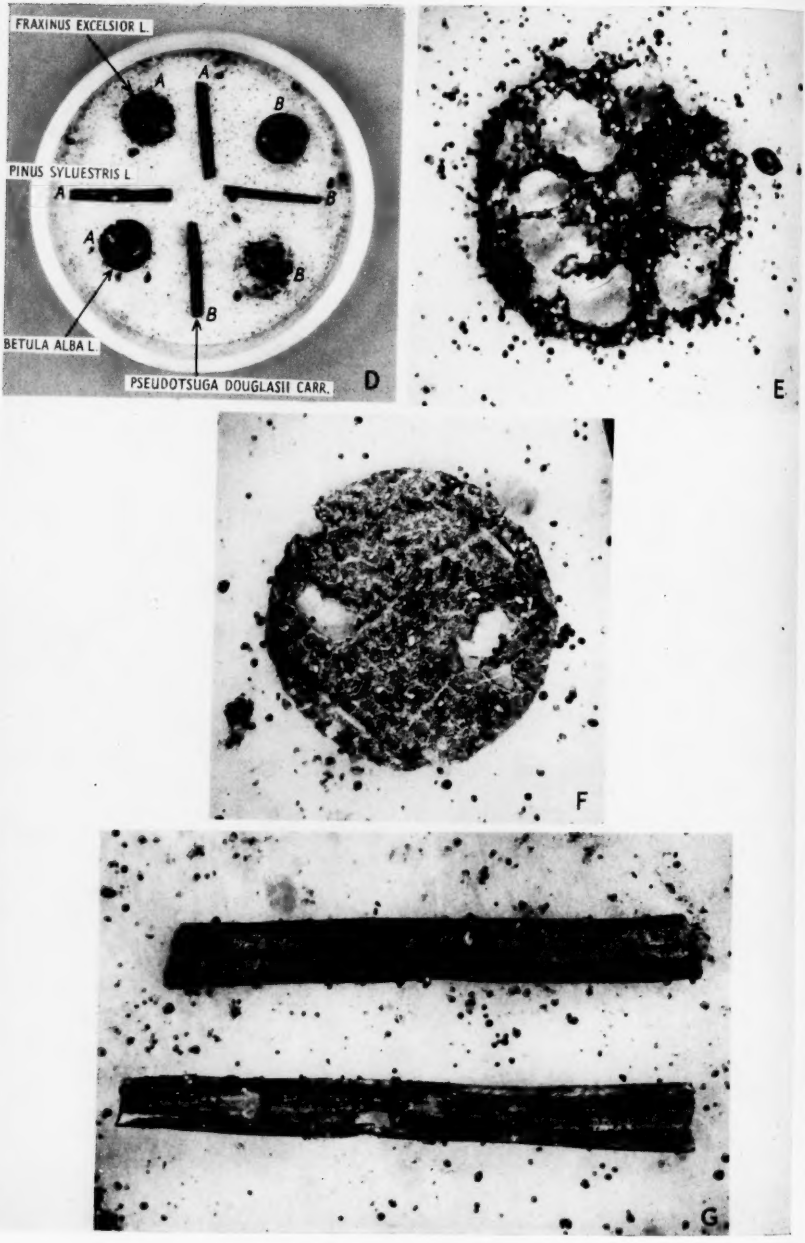
P. W. MURPHY—PLATE I



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P. W. MURPHY—PLATE II

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P. W. MURPHY—PLATE I

A. *Pseudotritia ardua* (C. L. Koch), a medium-sized oribatid mite of the family Euphthiracaridae. ×70.
B. *Pergamasus runcatellus* Berl., a large predatory mite of the Mesostigmata. ×50.
C. *Isotoma sensibilis* Tullberg, a common springtail inhabiting moss, &c. ×50.

P. W. MURPHY—PLATE II

D. Litter preferences of the mite *Steganacarus magnus* (Nic.) (*Hoploderma magnum* (Nic.)). Appearance of culture of 75 mites after 96 days. The dark specks are excrements of the mites. Disks: diameter 0·5 cm.; needles: length 1 cm. ×1½.
E. *Fraxinus excelsior* L. Disk A of D. ×9.
F. *Betula alba* L. Disk A of D. ×9.
G. *Pseudotsuga Douglasii* Carr. (top) and *Pinus sylvestris* L. Needles B and A respectively of D. ×9.

Photographs by P. W. Murphy and H. F. Woodward

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THE MICRO-MINERALOGY OF NORTH WALES SOILS

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WITH FOUR PLATES

1. *Introduction*

ABOUT three years ago the writer, who had for many years specialized in the microscopy of accessory minerals, was invited by the late Professor G. W. Robinson to undertake mineralogical examination of the soils of North Wales and to attempt to correlate their mineral assemblages with those of the 'Drift' and of the 'Solid' rocks of the region. The present paper is an account of some of the results obtained.

There is much published work on the petrology of the rocks of North Wales,[1] especially on the igneous and metamorphic rocks. When, however, efforts were made to trace the soil minerals back to the original rock materials in this region it was realized that this previous work, though it provided an essential guide for pedological work, had been directed towards Geology's own current problems and that much petrological groundwork of the kind needed to form a basis for detailed soil-mineral studies had yet to be done. Knowledge of the accessory minerals of most types of North Wales rocks was probably inadequate, because methods of separating mineral components by means of heavy liquids had not often been used to supplement the knowledge gained from the study of thin sections. The mineralogy of the Palaeozoic sedimentary rocks, though they give rise to soils of more practical interest than those derived directly from igneous and metamorphic rocks, had received much less attention, and the mineralogy of the Pleistocene deposits, though they cover most of the country that is not mountain-land, had been almost completely untouched.

It was planned, therefore, to give greatest attention to the Pleistocene, to make a limited study of the Palaeozoic, and to examine soil samples representing the more important soil series in North Wales. Most of the soil samples have been chosen from those collected in routine work by the Soil Survey of Wales (1930, 1932, 1935, 1939), though some have been collected by the writer with special problems of soil mineralogy in mind. Most of the samples are from Caernarvonshire and Anglesey, though some are from north-western Denbighshire and from Flintshire.

The usual methods of separation have been adopted. Most of the rocks were disintegrated by crushing without undue force in an iron mortar, but for calcareous rocks cold hydrochloric acid was employed. Heating with hydrogen peroxide has been used as a routine treatment for soils. Clay material has been removed by decantation and coarse material by passing through a 36 B.S. sieve. The heavy minerals have

[1] The general geology of the area has been described by Smith and George (1948). Details of the mineralogical composition of the rocks is given in papers by Harker (1889), Sargent (1915), Greenly (1919), H. Williams (1927), Billinghurst (1929), D. Williams (1930), and in other works referred to in the text.

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been separated by means of bromoform (sp. gr. = 2·9) in Spaeth separators. A few heavy residues in which abundant ferruginous matter hindered microscopic examination were given a final cleaning with hot hydrochloric acid.

The geological formations in this part of Wales belong to the Pre-Cambrian, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Triassic, and Pleistocene. In addition to the sedimentary formations there are metamorphic rocks (chiefly Pre-Cambrian and Cambrian), extrusive igneous rocks (Pre-Cambrian and Ordovician) and intrusive igneous rocks of widely different types (Fig. 1).

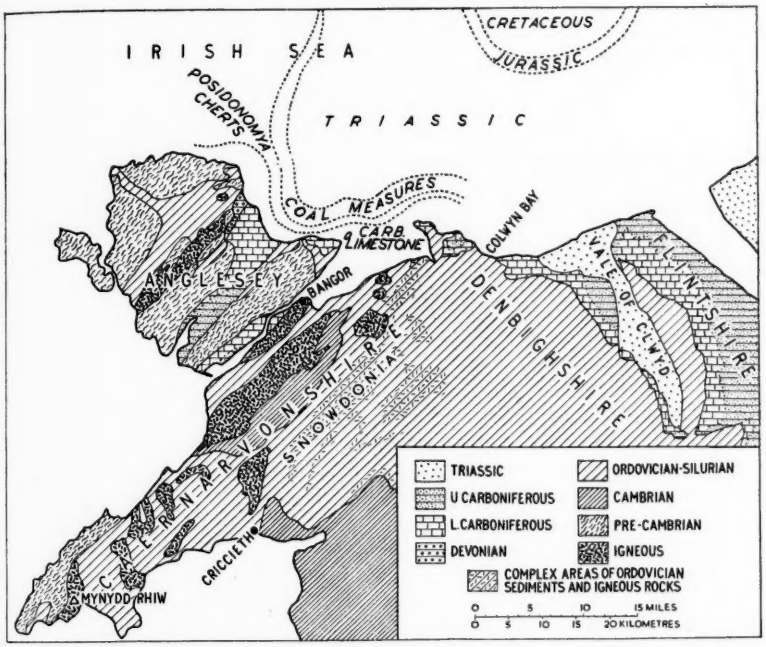

FIG. 1. Geological map of North Wales. Geology of land area simplified from Geological Survey Maps, hypothetical geology of sea-floor from Geological Survey Memoir (Greenly, 1919).

All these geological materials, as well as materials from more distant sources, have contributed to the soils, and the commonly accepted methods of classification of soils into series demands and implies a knowledge of the nature of these contributions. Each succeeding sedimentary formation has, of course, derived its material from some pre-existing rocks, but the pedologist is not concerned to know the complete petrological ancestry of each deposit, being usually content to record the position of the material in the stratigraphical sequence immediately prior to its utilization by soil-forming agents. For Pleistocene deposits, however, it has been his practice to attempt to trace the material one

step back, e.g. a Pleistocene deposit consisting of material derived from Triassic deposits. In the Soil Survey work in North Wales such inferences had always been made from general inspection of the deposits, but Professor Robinson considered that microscopic examination of the Pleistocene deposits should be undertaken as early as possible. A large number of samples were, therefore, collected from coast sections, sand and gravel pits, &c., in Anglesey and Caernarvonshire in order to study the minerals of the sand fractions. The complete results cannot be presented here, but the main facts of interest to pedologists can conveniently be presented at this point.

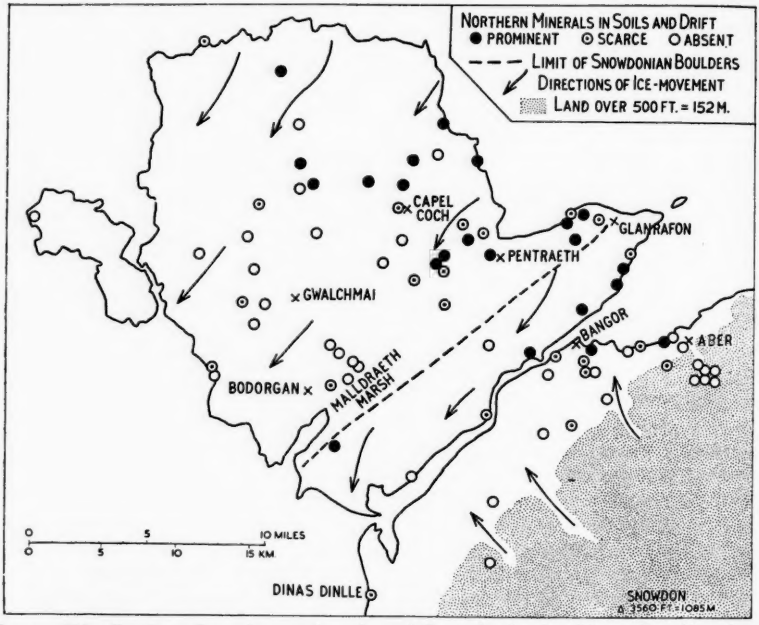

FIG. 2. Distribution of northern minerals and Snowdonian boulders. Ice directions in Anglesey and distribution of Snowdonian boulders, after Greenly (1919).

2. *Pleistocene Deposits*

The general mode of formation of these deposits in North Wales is not a matter of dispute. It is agreed that ice invaded the area from the north and that the mountains of Snowdonia diverted the direction of movement towards the south-west over the peneplain of Anglesey. Some of the Glacial Drift consists of material carried from both near and distant sources by the northern ice sheet, some consists of Snowdonian material brought down by movements in the local ice-cap, and there is a belt where the two ice-streams have mingled their deposits. The approximate distribution of Snowdonian erratics in the boulder clays has been mapped by Greenly (Fig. 2), and the microscopic examination of the inter-glacial and post-glacial sands and of the sand fractions

of the boulder clays has shown somewhat similar lateral variations. The mineral assemblages to be expected in drift derived from Snowdonian rocks can be learned from the geological literature and from the contents of stream sands. It can thus be shown that the glacial deposits lying close to the mountains contain few minerals which cannot be attributed to this source. In contrast with these, the boulder clays along the north-east coast of Anglesey contain minerals which are unknown in Snowdonia, and which since the ice-movement was from the north and north-east, could not have been derived from rocks on the Anglesey land surface. The minerals which are the most valuable indicators of the northern influence are staurolite, andalusite, and kyanite (Plate I, A). There do not appear to be any records of kyanite in the 'solid' rock of North Wales, but andalusite and staurolite are noted by Greenly as occurring in the Pre-Cambrian of Anglesey. Nevertheless there is little doubt that for all three minerals the source of the grains found in the drift is predominantly northern (Fig. 2).

The primary source of the staurolite, andalusite, and kyanite must be metamorphic rocks, but the ice-sheet may have brought them, in part, from some of the younger sedimentary rocks (Mesozoic or Tertiary). Greenly (1919, p. 778) from his study of the pebbles in the Glacial deposits concluded that an area of Mesozoic sediments exists on the floor of the Irish Sea (Fig. 1). Staurolite is common in some areas of Triassic rocks in the British Isles, but andalusite is scarce in sediments older than the late Tertiary. Fig. 2 shows that these minerals have reached the lower ground of the north Caernarvonshire coast and are conspicuous in the north-eastern part of Anglesey, but over the remainder of the island they become very scarce owing, no doubt, to large additions of material derived from Anglesey rocks.

It should be pointed out that in Anglesey the dominant direction of ice-movement (NE. to SW.) is also the dominant trend of outcrops over much of the island. As a result, the material which the ice picked up from the rocks of Anglesey suffered much less mixing than occurred where no such simple relationship existed.

Greenly (1919, 1942) classified the Glacial deposits of Anglesey and Caernarvonshire, the following being the main divisions:

(4) Esker Gravels
(3) Upper Boulder Clay ('Red Boulder Clay')
(2) Inter-glacial Sands and Gravels
(1) Lower Boulder Clay ('Blue Boulder Clay')

but of these divisions only the esker deposits and the Upper Boulder Clay are exposed sufficiently to be of much pedological importance.

The degree of variation in the Pleistocene deposits has been stressed, yet they all have one feature in common—the presence of certain relatively unstable minerals which are absent from the older sediments. Fig. 3 represents graphically the frequency of occurrence of only seventeen of the thirty or so heavy minerals which have been found in the Pleistocene deposits; if the complete list of mineral species were used the contrast between the older and younger sediments would be more striking still. The fact that young sedimentary deposits are on the whole

richer in mineral species than the more ancient ones has been realized for many years, but it was at one time thought that this could be adequately explained by assuming that successive phases of igneous activity, crustal movements, and cycles of erosion throughout geological time had progressively increased the variety of minerals available on the exposed land surfaces, so producing more varied assemblages in detrital

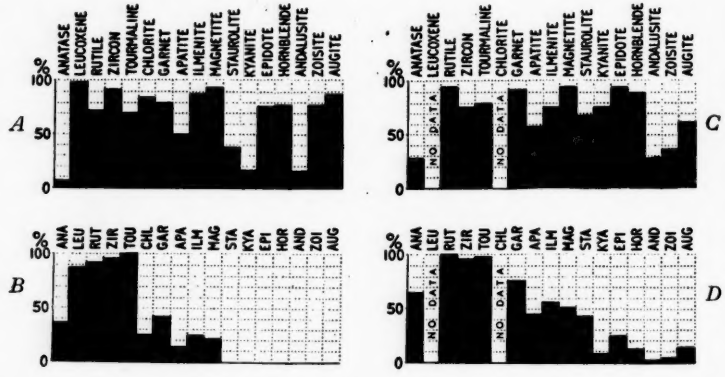

FIG. 3. Frequency of minerals in Pleistocene and Palaeozoic sediments. A. Pleistocene, Anglesey and Caernarvonshire. B. Sandstones and grits of Carboniferous age, North Wales. C. Pleistocene, world-wide, from Pettijohn's data (1941). D. Devonian, Carboniferous and Permian, world-wide, from Pettijohn's data. The columns indicate the percentages of samples in which each of seventeen important minerals are present. The minerals are arranged as in Pettijohn's stability series, with the more stable minerals to the left. Leucoxene and chlorite, for which Pettijohn gives no data, are given provisional positions.

deposits. It is now recognized that many ancient sedimentary deposits must originally have possessed richer assemblages than those which we find in them today, the present paucity of minerals being due, in part at least, to the progressive decomposition of the unstable ones (Pettijohn, 1941; Smithson, 1939, 1941). This question of mineral stability and the attempts to arrange minerals in 'stability series' is as important to the pedologist as it is to the petrologist, but for more detail readers must be referred to a recent summary (Smithson, 1950). Pettijohn's stability series has been used in deciding the sequence of minerals in the histograms in Fig. 3, and this device clearly gives a useful mathematical turn to such diagrams since to some extent both ordinates become quantitative.

Among the unstable minerals of the Pleistocene deposits of North Wales, augite is particularly characteristic. The considerable degree of corrosion which has taken place, especially in many of the coarser interglacial sands, is shown by the extremely deep indentation of the grains, which often exhibit a form so delicate that they could not have existed in this condition at the time of transport (Plate I, B).

The classification of glacial drift employed by the Soil Survey does not follow the stratigraphical divisions of Greenly which have been men-

tioned above, but specifies the deposits as 'material derived from Triassic rocks', 'material derived from Carboniferous Limestone', and so on. In all cases, however, the present microscopical study reveals the occurrence of augite and many other unstable minerals which we know could not have been supplied by any of these older sediments, nor formed by the alteration of any of the minerals in them. Material from sources other than those specified must therefore be present, e.g. the augite may be derived partly from local and partly from more distant basic igneous rocks, or possibly from Tertiary deposits on the floor of the Irish Sea.

The heavy residue (sp. gr. $> 2{\cdot}9$) from a typical Pleistocene deposit is usually small compared with the light portion (sp. gr. $< 2{\cdot}9$) of the sand fraction; and yet it is very many times larger than the heavy residue normally obtained from the older arenaceous sediments (e.g. Carboniferous). Such quantitative evidence again suggests that the drifts must, in general, derive part of their material from rocks richer in heavy minerals than these old sediments. It is evident, however, that a small amount of detritus from, say, a basic igneous rock of which something of the order of 50 per cent. may consist of heavy minerals will make a disproportionately large change in the heavy mineral assemblage when added to the material from a Carboniferous rock whose heavy minerals may amount to very much less than 1 per cent. Thus the heavy residue may sometimes be too sensitive an indicator of contamination and a study of the light fractions, though they usually present fewer distinctive features than the heavy residues, may provide a better means of judging in what proportion the materials from several sources have been mixed. For example, in glacial deposits at College Farm, Aber, rounded grains of quartz are common (Plate I, c), a fact compatible with the view that these deposits have derived most of their arenaceous material from the desert-formed sandstones of the Trias, although the bulk of the heavy residue is non-Triassic.

One further important result of the Pleistocene glaciation must be mentioned, namely, the removal of the pre-existing weathered material from the Pliocene land surface at the beginning of Pleistocene times and the production of the clean unweathered rock-platforms often seen where the glacial cover has been recently removed. It is often quite evident, as for example in the case of glaciated surfaces of Lower Carboniferous grits in Anglesey, that the rock has suffered no appreciable weathering since Glacial times. In the case of the limestone surfaces under thin sandy drift the amount of weathering has probably been greater, though it has been insufficient to contribute much insoluble residue for soil formation.

3. *Soil Series defined Petrologically*

(*a*) *Soils derived from basic igneous rocks*

Soil Series: *Rhiw.*

Soils of this series have been mapped over a small area at Mynydd Rhiw in south Caernarvonshire (Soil Surv. Wales, 1939), the parent material being recorded as colluvium derived from quartz dolerite. The

mountain, Mynydd Rhiw, is shown on Geological Survey maps as a single mass of basic igneous rock, but Matley (1932) has shown that the structure is more complex than this and that some beds of sedimentary rocks are present. Nevertheless the mineralogy of the profile examined differs little from that which would be expected from a soil derived from doleritic material.

The sand fraction is unusual in that the major portion of it sinks in bromoform. The small light fraction contains quartz grains (mostly angular), altered felspar, and a mineral which may be serpentine. The heavy residue consists almost exclusively of amphiboles and pyroxenes, both having the form of unworn cleavage fragments, though the latter shows some evidence of decomposition in the etched outlines (Plate I, D). In the upper part of the profile there are a few well-rounded grains of quartz, otherwise the soil shows no mineral grains which could not have been supplied by the quartz dolerite.

(*b*) *Soils derived from acid igneous rocks, hard siliceous sediments and slates*

Soil Series: *Bangor*, sedentary; *Arvon* (or *Arfon*); *Deiniol*; *Eivion* (or *Eifion*).

Rocks of the above-named types occur in North Wales in the Pre-Cambrian, Cambrian, and Ordovician systems, and the soil series are mapped extensively in Caernarvonshire and Anglesey. Nineteen soil samples have been examined, including seven formerly classed as *Penrhyn* or *Cegin* (Section IV. 2).

A soil of the *Bangor* series, sedentary on Coedana granite in Anglesey contained no minerals inconsistent with its being a pure sedentary soil derived from such a rock. *Arvon*, *Deiniol*, and *Eivion* soils all contained augite, probably derived from basic dikes, and there were other minerals not to be expected from the putative parent rocks (Plate I, E and F).

The rocks named in the definition possess important features in common—a rather high SiO_2-content and a high resistance to chemical weathering and mechanical breakdown—yet they are widely different in origin and would be expected to supply widely different mineral assemblages to their respective soils. Such, indeed, appears to be the case, and it is evident that no useful conclusions can be drawn until both the soils and the rocks in question have been more extensively studied.

4. *Soil Series defined Stratigraphically*

(*a*) *Soils derived from Pre-Cambrian schists and gneisses*

Soil Series: *Cybi*, podzol; *Anglesey*, sedentary; *Gaerwen*; *Trisant*; *Gesail*; *Braint*.

The Pre-Cambrian rocks, which occupy a large part of Anglesey, have contributed considerably to the drift deposits and soils, especially in the south-western half of the island. They consist mostly of rather slow-weathering rocks relatively rich in silica, but there are some basic portions, which consist in some places of igneous and in others of metamorphosed igneous rocks, and which occur here and there throughout the more acidic members. The mineral composition is known to vary

considerably from one stratigraphical horizon to another within the Pre-Cambrian complex, and also laterally along the stratigraphical horizons (Greenly, 1919). Hence the mineral assemblages to be expected would need to be considered individually at each site. Extreme variability from place to place has indeed been noticed in the eight samples studied. The augite, present in all samples and predominant in one of the heavy residues, may be derived from the basic rocks within the complex. In a *Gaerwen* soil in an area of glaucophane schists the mineral glaucophane was found to be very abundant, and in the south of the island and on the mainland still farther south this mineral is present in the drifts. In a *Trisant* soil unworn grains of epidote were the predominant mineral. The relationship of the soils to the Pre-Cambrian rocks is thus seen to be a complicated one requiring extensive work for its elucidation.

(*b*) *Soils derived from Lower Palaeozoic shales*

Soil Series: *Powis* (or *Powys*), sedentary; *Penrhyn*; *Sannan*; *Cegin*; *Conway*.

A great part of the Lower Palaeozoic rocks of North Wales consists of non-calcareous argillaceous rocks—shales, mudstones, and siltstones—sufficiently similar for the pedologist to group them together as giving rise to one suite of soils. There are no published accounts of the accessory minerals of these rocks except for the Middle Silurian rocks of Denbighshire from which Boswell (1949) has recorded restricted mineral assemblages, with chlorite as the commonest heavy mineral. The heavy assemblages obtained from the soils in many cases consist almost entirely of opaque minerals (limonite, ilmenite, magnetite, and leucoxene) and relatively large flakes of pale green chlorite with rather rounded outlines (Plate II, A, B, and C). It is difficult to obtain similar flakes from the unweathered shales, since chlorite, unlike most of the accessory minerals, is much torn and distorted in the process of rock crushing. If, however, small pieces of soft weathered shale are separated from the subsoil they may yield almost undamaged flakes after gentle crushing. In some of the shales there is much pyrite which would not survive in the soil but is probably the source of some of the limonite.

Many of the soils classed in these series contain material which is certainly not derived from the shales (Plate II, D). The extent to which such foreign material is present in the heavy residue may be roughly indicated by recording the 'richness' of the residue, i.e. the number of mineral species present (Table 1). The smallest heavy mineral assemblages contain only such minerals as could have been supplied by the shales, e.g. a *Cegin* soil from Denbighshire contained only chlorite, leucoxene, limonite, magnetite, rutile, and zircon. In the richer assemblages augite and hornblende are the most persistent contaminants. In south Caernarvonshire and in Anglesey, where the amount of foreign material reaches the greatest proportions, contamination is due partly to the influx of northern minerals and partly to the presence of minerals from local igneous and metamorphic rocks.

TABLE I

Richness of Heavy Mineral Assemblages in Powis *and Related Soils*

	Denbighshire	*S. Caerns.*	*Anglesey*
Powis . .	7, 8, 9	7, 10	11
Penrhyn . .	6, 8, 9, 11, 11, 11	14, 14	10, 12, 13, 15, 16
Sannan . .	. .	. .	13
Cegin . . .	6, 7, 7, 9	14, 14	14, 17
Conway . .	10	. .	. .

Note: The numerals indicate how many heavy mineral species have been observed in each of the soil samples. For example, from the *Powis* series of Denbighshire three samples have been examined, and these contained 7, 8, and 9 heavy mineral species respectively.

Differences are also noted in the light minerals of the sand fraction. In some of the soils the light grains of sand size consist almost entirely of shale particles (Plate II, E). In others, typical quartz sand grains are common, and in some of the non-sedentary examples in south Caernarvonshire and Anglesey they are much more numerous than the shale particles.

(*c*) *Soils derived from Devonian sediments*

Soil Series: *Monmouth* (not examined), sedentary; *Castleton*; *Marshfield* (not examined); *Frogmoor*.

Devonian sediments, mostly of a reddish colour, occur in a small area in Anglesey (Fig. 1). They are described by Greenly (1919, p. 578) as consisting of rocks of the following types: conglomerates; sandstones, most of them rather fine grained; still finer-grained non-calcareous sediments classed as mudstones, 'marls' or 'dust-rocks'; fine calcareous sediments known as 'cornstones', in which the calcite is in small concretions which give rise to cavities as the rock weathers; and massive limestones which differ from the other members of the system by being grey in colour.

Unfortunately the petrological information regarding these rocks is at present very inadequate. One sample of cornstone has been examined and the minerals present after acid treatment are leucoxene, ilmenite, magnetite, haematite, zircon, rutile, tourmaline, and chlorite. Greenly (1927) described the heavy minerals from a sample of sandstone in which most of the above minerals were present and, in addition, barytes, biotite, brookite, epidote, and garnet. In a sample of the dust-rock he recorded a less extensive assemblage.

Soils of the *Castleton* and *Frogmoor* series are reddish in colour. Three of the former and one of the latter have been examined and the heavy residues do not suggest the presence of much material that could not have been derived from the Devonian rocks (Plate II, F). Some staurolite, amphibole, pyroxene, and andalusite have been found and these are certainly foreign, but they are much less common than the foreign minerals which have found their way into some of the soils attributed to the Carboniferous and Triassic rocks.

(*d*) *Soils derived from Lower Carboniferous rocks*

Soil Series: *Gower*, sedentary; *Pentraeth*; *Hendre*; *Dyfnan*.

The Lower Carboniferous rocks consist of limestones (often dolomitic), shales (often highly calcareous), and siliceous rocks ranging from fine sandstones to conglomerates. To determine what minerals these rocks are likely to contribute to the sand fraction of a soil the dominantly calcareous rock samples have been treated with cold hydrochloric acid and the remainder have been crushed and sieved, followed by heavy liquid separation in all cases except those of limestones with extremely small sand fractions.

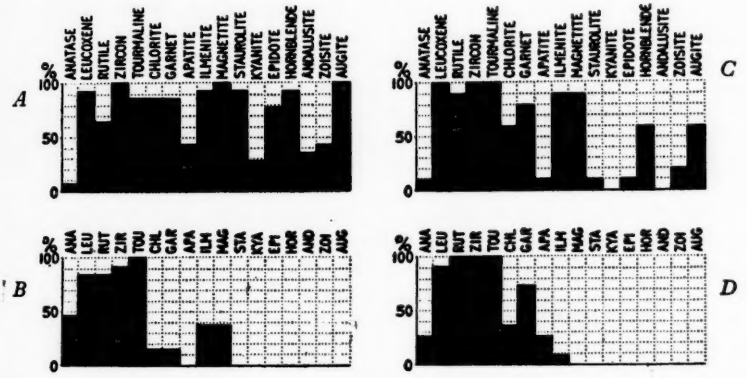

FIG. 4. Frequency of minerals in Carboniferous sediments of North Wales and their related soils. A. Soils classified as derived from Lower Carboniferous sediments. B. Sandstones and grits of Lower Carboniferous age, including data by Boswell (Greenly, 1928). C. Soils classified as derived from Millstone Grit. D. Millstone Grit.

The sandstones contain few species of heavy minerals, the chief being leucoxene, zircon, rutile, and tourmaline (Fig. 4, B). Pyrite crystals or limonite pseudomorphs of these crystals are often very common. Magnetite and ilmenite are either scarce or absent, but anatase, a mineral which can form in a sediment as a result of the decomposition of other titanium-bearing minerals, is often present in small amounts. Garnet and chlorite are occasionally present, and an unusual type of tourmaline grain, showing corrosion at one end and secondary growth on the other, is common (Plate III, A and B). Some of the sandstones may have been rich in felspar, but the light fraction now consists of little but quartz, and unusually large crystals of a clay mineral. Samples of this clay mineral have been separated by decantation methods, and Mr. G. Brown of Rothamsted has made X-ray examinations of this material and of a similar sample from the Millstone Grit, obtaining from both samples diffraction patterns indicating dickite as the dominant mineral. The crystals are hexagonal in shape, some being almost regular hexagons. The diameters are mostly from 10 to 30 microns. In some cases a large number of plates stand together on edge in the slide forming elongated bodies sometimes described as rouleaux.

The insoluble residues from calcareous beds vary greatly both in form and amount. In one case there was nothing but haematite dust and a little chert. Detrital quartz was absent from many of the samples, silica being present mostly as chert either in the form of irregular growths (Plate III, D) or, less commonly, in the form of small fossils such as sponge spicules or minute gastropods (Plate III, E). Small perfectly shaped crystals of quartz were present in the majority of the samples, but in only one case were they numerous. Heavy minerals were sometimes completely absent, but in one impure limestone as many as seven heavy mineral species were recorded. Finely divided pyrite is probably dissolved by the acid, but crystals of pyrite survive the treatment and are seen in a few samples. It is clear that for many of the limestones a very large amount of rock would need to be dissolved by chemical weathering to give an appreciable amount of clay, silt, or sand for the formation of a soil. Any soil formed in this way should be more readily recognized by its light fraction than by its heavy detrital minerals, but being so small in amount, the total contribution from the solution of the limestone would be readily obscured if there was any slight contamination from other sources.

From the above description it is evident that the sand fraction of any soil derived exclusively from these Carboniferous limestones would possess several distinctive features, the light fraction consisting of chert and crystals of quartz rather than detrital quartz grains, and the heavy fraction being small and poor in mineral species. The introduction of material from the sandy beds of Lower Carboniferous age would add much detrital quartz but would increase only slightly the quantity and richness of the heavy residue. The soils of the *Gower*, *Pentraeth*, and *Dyfnan* series, however, have yielded much richer assemblages of minerals than the rocks in question (Fig. 4, A and B; Plate III, G) and it is clear that their sand fractions owe much to some kind of mixed drift of northern origin.

Only small patches of ground have been mapped as the sedentary *Gower* series. Soil Survey samples from a profile in one such patch at Llysfaen near Colwyn Bay yielded a heavy residue with fourteen different mineral species, i.e. twice as many as in the richest limestone examined, and grains of detrital quartz formed the major part of the light fraction. A *Pentraeth* soil close at hand showed sixteen different species in the heavy residue, which was unusually rich in well-preserved grains of andalusite, many of them clearly belonging to the variety known as chiastolite because of the X-shaped area of dark inclusions (Plate III, C).

On Anglesey, soils of these series contain some material presumably derived from the Carboniferous rocks, e.g. sponge spicules consisting of chert were present in four cases (Plate III, F), grains of calcite in two and hexagonal plates, which are probably dickite, in one. Among the tourmaline grains a small proportion showed the secondary growths mentioned above. To sum up, it is safe to say that there is some material of Carboniferous origin, that much is definitely not of Carboniferous origin, whilst perhaps the major portion should not be assigned to either category without more exhaustive study.

It would be of interest to determine the precise geological description of the parent material of these non-sedentary soils, but this has not yet been done. Some of the *Hendre* soils are evidently developed on late Pleistocene gravels classed by Greenly as Esker gravels (Section II), and Terrace gravels. In one gravel from a pit at Pentraeth about a quarter of the pebbles were found to be limestone.

Near the eastern tip of Anglesey the Carboniferous limestones and Pre-Cambrian green schists are thinly covered with what appears to be identical types of drift. In one place where a thin soil rested upon a very pure limestone it was clear from the microscopical examination that the weathering of the rock had contributed a negligible amount of insoluble matter to the soil and that the sand fraction of the soil was identical with that of the northern drift (Plate III, H). Where the thin drift rests on the schist it has developed into an acid soil with tendencies towards podzolization, whilst the soil on the limestone exhibits the features of a rendzina. Such a soil looks like a sedentary soil and from field inspection the underlying limestone would doubtless be regarded as the parent rock. Nevertheless microscopical investigation suggests that the rock is more in the nature of a foster-parent that has imparted to the profile the characteristics of a limestone soil.

(*e*) *Soils derived from the Millstone Grit formation*

Soil Series: *Bodkin*, sedentary; *Treuddyn* (or *Tryddyn*); *Nercwys* (or *Nerquis*); *Talog*.

The most extensive occurrence of this part of the Upper Carboniferous is in Flintshire, but there is a small area of great interest in Anglesey. As regards their mineral content the grits are in many ways similar to those of the Lower Carboniferous (Fig. 4, D), but there are certain differences, some of which are of importance to the pedologist.

In Anglesey the heavy residues are somewhat richer in mineral species than those from the Lower Carboniferous grits, and dickite is more abundant. The heavy minerals apatite and monazite are sometimes conspicuous, and although the former might soon disappear in an acid soil derived from the rock, the latter should survive to contribute some evidence of parentage. Garnet is usually present, always showing signs of severe corrosion, and ankerite, the mixed carbonate of calcium, magnesium, and ferrous iron, occurs as a cementing material in some parts of the rock. Kaolin (now identified as the variety dickite) is said by Greenly (1919, p. 661) to form as much as 25 per cent. of the volume of the rock, but as the mineral is light and 'fluffy' this statement may give a false impression of the amount. A sample from Bodorgan shore, when gently broken up and shaken on a 120 B.S. sieve, yielded a powder which amounted to 10 per cent. of the weight of the rock, and Mr. G. Brown estimated by X-ray methods that not more than one-twentieth of this powder consisted of quartz. The crystal plates measured from 10 to 50 microns across, and the rouleaux although they break up readily have been found up to 40 microns in length (Plate IV, A).

Some heavy residues from Flintshire, on the other hand, were distinctly impoverished and little dickite was detectable microscopically.

The Millstone Grit formation though not a marine deposit contains marine bands, and a sample of such a bed from Nercwys Mountain has yielded a great abundance of sponge spicules (Plate IV, B), thus explaining the presence of spicules in *Treuddyn* soils of the neighbourhood.

The micro-fossils are usually in the form of chert and thus appear in the light fraction. Yet some fragmentary micro-fossils from the marine-band sample appear in the heavy residue and fragments very similar in appearance have been found in a *Talog* soil from Anglesey. The fossils have not yet been identified, but the material appears to be ankerite.

A sedentary soil on the Millstone Grit of Nercwys Mountain (site altitude about 1,100 ft. = 335 m.) has yielded a heavy residue containing few mineral species, all of which could have been provided by the underlying rock. In contrast with this, *Treuddyn* and *Nercwys* soils from both Flintshire and Anglesey contain appreciable quantities of mineral grains which could not have come from the Millstone Grit. Amphiboles and pyroxenes are present, occasionally abundant, in the heavy residues (Plate IV, C); and magnetite and ilmenite, which are usually absent from the grits, are usually present in the soils. Small hexagonal plates resembling the crystals identified in the grits as dickite have been observed in a *Treuddyn* soil in Anglesey. An Anglesey *Talog* soil yielded a flood of the mineral barytes (Plate IV, D), probably indicating a local occurrence of this mineral as a cementing material or possibly as veins in the grit. Samples of a *Treuddyn* soil at Treuddyn in Flintshire contain extremely numerous flakes of pale green chlorite similar to those observed in *Powis* and related soils (Plate II, A, B, and C). Since this mineral has not yet been found in the Millstone Grit formation in this county one is led to ask whether the neighbouring Lower Palaeozoic rocks have contributed to these soils. Chlorite has been found in the Millstone Grit of Anglesey, but here the mineral is a deeper green and has not the well-rounded outline of the *Powis* chlorite.

Fig. 4, C and D, indicates that these soils are in general richer in heavy mineral species than the rocks in question. The contrast is, however, less conspicuous than in the case of the Lower Carboniferous rocks and their related soils, due to the fact that in the areas where the Millstone Grit occurs there happens to have been less invasion by northern minerals. For example, in Anglesey the Lower Carboniferous rocks occur around Glanrafon and in the broad coastal area which runs northward from Pentraeth (Fig. 2) whilst the Millstone Grit is confined to a small area near the Malldraeth Marsh.

(*f*) *Soils derived from Triassic sediments*

Soil Series: *Newport*; *Flint*; *Salop*.

Triassic sediments occur in the Vale of Clwyd, but most of the material forming the reddish Upper Boulder Clay and the reddish Interglacial sands have generally been regarded as derived from Triassic rocks of the Irish sea area.

The mineralogy of most of the Triassic areas in the British Isles was studied in the early days of heavy mineral studies and has been summarized (Smithson, 1931). The most important features of the heavy

mineral assemblages in the Vale of Clwyd, taken mostly from the data of Double (1927), are shown in Fig. 5, B. In other areas the assemblages are similar except that apatite, staurolite, and garnet are often much commoner. Double (1928) has listed minerals found in Triassic pebbles in the Boulder Clay of Anglesey but has given no data of their abundance or persistence. In three such pebbles collected and examined by the writer only ilmenite, magnetite, leucoxene, zircon, rutile, tourmaline, and apatite appeared to be common. Yet even if we suppose that the Irish Sea Trias has an assemblage as rich as any in the British Isles, this will not account for the composition of the sand fraction in the *Newport*, *Flint*, and *Salop* soils, particularly for the persistence of augite and epidote (Fig. 5, A).

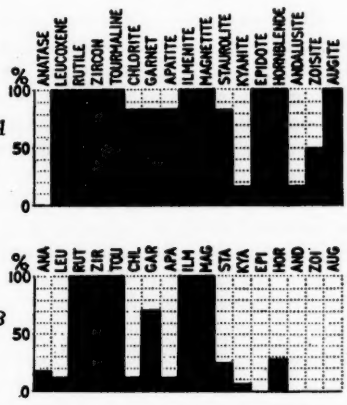

FIG. 5. Frequency of minerals in Triassic sediments of North Wales and their related soils. A. Soils classified as derived from Triassic sediments. B. Triassic sandstones, based on data given by Double (1927) and on samples collected by the Soil Survey.

The presence of non-Triassic material is shown not only by the occurrence of particular species but by the shape of the grains. The grains in the Trias tend to be well rounded (Plate IV, E), and the grains of the same mineral species in the soil are for the most part well rounded also. Grains of augite, however, in the soils are mostly angular (Plate IV, F), their boundaries determined by cleavage and fracture except where modified by corrosion.

The reddish Upper Boulder Clay of Anglesey bears soils which are classed as *Flint* and *Salop*. Among the pebbles only a small proportion appear to be Triassic, but since the Triassic rocks are soft it would be expected that their chief contribution would be to the finer fractions. Yet even in the sand fraction, coal fragments (Carboniferous?), flint or chert (Carboniferous? Cretaceous?) and shale fragments (Carboniferous? Ordovician?) are found, and one receives the impression that the Upper Boulder Clay and the soils derived from it are of very mixed origin.

5. *Conclusion*

The microscopical studies of soils and rocks in North Wales described in this paper have been directed towards determining and explaining the mineralogical composition of the sand fractions of most of the important soil series. The mineralogical composition of the sand fraction and the composition that would be expected from the weathering of the rock cited in the definition of the soil series have been compared; and close agreement has been found in only a few cases, namely, (*a*) some sedentary and non-sedentary soils derived from Lower Palaeozoic shales, (*b*) one soil sedentary on Millstone Grit, and (*c*) one soil whose parent material

was colluvium derived from a basic igneous rock. In all other North Wales soils examined there is considerable contamination, usually due to Pleistocene glaciation.

Even in the presence of such contamination it is often possible to recognize what contributions have been made to the sand fractions by the local solid-rock formations. In some of the soil series, however, the range of postulated parent materials is so wide that much work needs to be done before the mineral assemblages within each soil series can be defined with the necessary degree of exactitude.

No work has been done on the clay minerals except in the case of dickite, which it has been possible to observe microscopically where it occurs in a relatively coarse form and not, in the physical sense, as a clay.

Most of the minerals dealt with in an investigation of this nature have a high resistance to chemical change and therefore provide little in the way of plant nutrients. The very stable minerals, however, are of importance in pedogenic studies in so far as they occur with alterable minerals and act as indestructible 'labels' accompanying the changing material. It is true that during the formation of a non-sedentary soil the labels may have become displaced by the sorting action of a transporting agent, yet grains of the size such as those dealt with in this paper will be much less prone to this fault than the stones which are commonly treated as labels when studying soils in the field.

Acknowledgements

It was necessary that this geological work should be carried out in close co-operation with pedologists familiar with the area. Professor G. W. Robinson unfortunately did not live to help in the later stages when results were accumulating and their interpretation had to be undertaken. The writer has therefore been grateful that Mr. R. I. Davies of the School of Agriculture, Mr. Evan Roberts formerly of the Soil Survey of Wales, and Mr. J. F. Harrop at present officer of the Soil Survey in North Wales have been very ready to help and to discuss problems connected with the work and the presentation of the results. A Soil Survey Memoir and a soil map of Anglesey are now in course of preparation, and samples collected in connexion with this work have kindly been made available for work in connexion with the present paper.

On geological matters the writer has benefited from discussions with Professor P. G. H. Boswell and the late Dr. E. Greenly.

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KEY TO PLATES

All the photomicrographs were taken with ordinary illumination except where it is indicated that a phase-contrast system was used (Smithson, 1948).

PLATE I

A. Heavy minerals from Glacial sand, College Farm, Aber, Caerns. ×72. K, kyanite.

B. Heavy minerals from Glacial sand, Dinas Dinlle, Caerns. ×81. A, corroded augite.

C. Light minerals from Glacial sand, College Farm, Aber, Caerns. ×48. Chiefly rounded quartz.

D. Heavy minerals from *Rhiw* soil, Mynydd Rhiw, Caerns. ×66. Chiefly hornblende and augite.

E. Heavy minerals from *Arvon* soil derived from porphyritic rhyolite, near Mynytho, Caerns. ×66. A, corroded augite; C, chlorite; Z, zircon.

F. Heavy minerals from *Deiniol* soil derived from Coedana granite, SW. of Gwalchmai, Anglesey. ×66. Much hornblende and augite.

PLATE II

A. Heavy minerals from *Powis* soil, near Criccieth, Caerns. ×81. Opaques and chlorite.

B. Heavy minerals from *Powis* soil, near Eglwys Fach, Denbighs. ×81. Chiefly chlorite.

C. Heavy minerals from *Penrhyn* soil, Eglwys Fach, Denbighs. ×81. Chiefly chlorite; Z, zircon.

D. Heavy minerals from *Penrhyn* soil, near Llanerchymedd, Anglesey. ×66. C, chlorite; H, hornblende.

E. Light minerals from *Powis* soil, near Criccieth, Caerns. ×72. Shale fragments.

F. Heavy minerals from *Castleton* soil, Capel Coch, Anglesey. ×81. Opaques and zircon.

PLATE III

A, B. Tourmaline from Lower Carboniferous sandstone, near Bangor. ×108. Showing corrosion at one end and accretion at the other (darker) end.

C. Andalusite (var. chiastolite) from *Gower* soil, Llysfaen, near Colwyn Bay. ×42. Showing dark centre and one arm of the dark cross.

D. Chert from Carboniferous Limestone, Glanrafon, Anglesey. ×126. Phase-contrast.

E. Chert from Carboniferous Limestone, Treborth, Caerns. ×6. Reflected light. Irregular grains and micro-fossils.

F. Light minerals from *Pentraeth* soil, Llanbedr Goch, near Pentraeth, Anglesey. ×81. Showing sponge spicule composed of chert.

G. Heavy minerals from *Pentraeth* soil, Llanbedr Goch, Anglesey. ×42. Opaques, zircon, augite, garnet, tourmaline, &c.

H. Light minerals from thin soil on Carboniferous Limestone, west of Glanrafon, Anglesey. ×84. Phase-contrast. Rounded quartz derived from Glacial drift.

PLATE IV

A. Dickite from Millstone Grit, Bodorgan shore, Anglesey. ×375. Phase-contrast. R, rouleau of dickite.

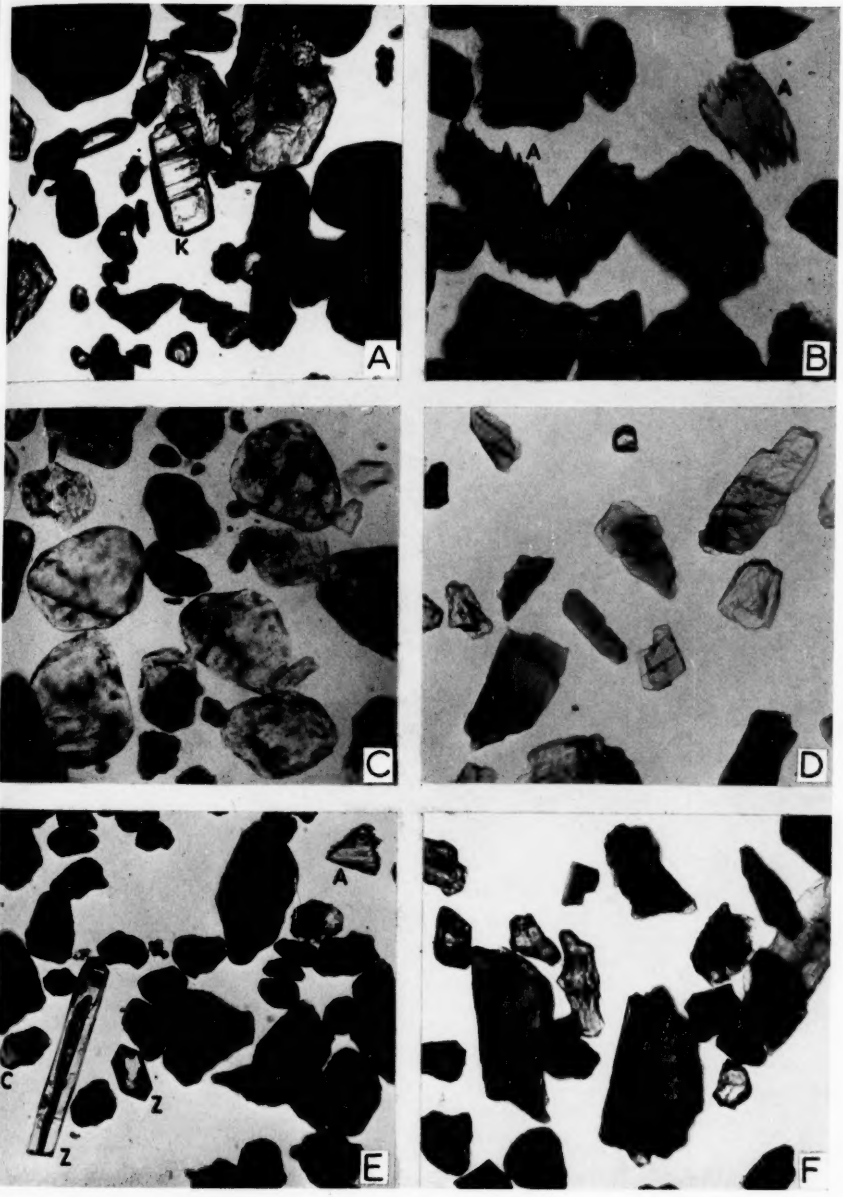
B. Chert particles, some in the form of sponge spicules, from marine band in Millstone Grit, Nercwys Mountain, Flints. ×105. Phase-contrast.

C. Heavy minerals from *Treuddyn* soil, NW. of Malldraeth Marsh, Anglesey. ×81. A, corroded augite.

D. Heavy minerals from *Talog* soil, NW. of Malldraeth Marsh, Anglesey. ×81. A, augite; B, barytes.

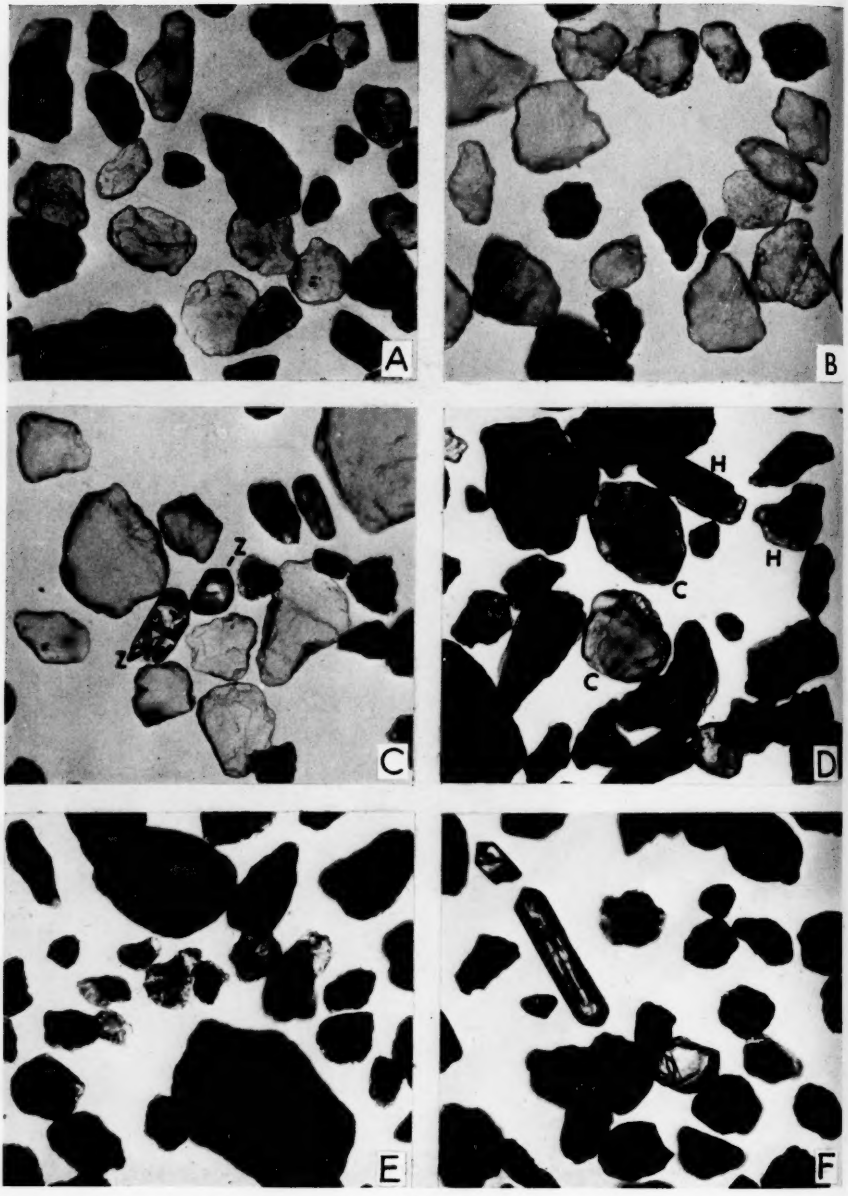
E. Heavy minerals from Triassic sandstone, Vale of Clwyd, Flints. ×42. Chiefly rounded opaques (iron ores).

F. Heavy minerals from *Newport* soil, Vale of Clwyd, Flints. ×66. Opaques, zircon, tourmaline, angular augite.

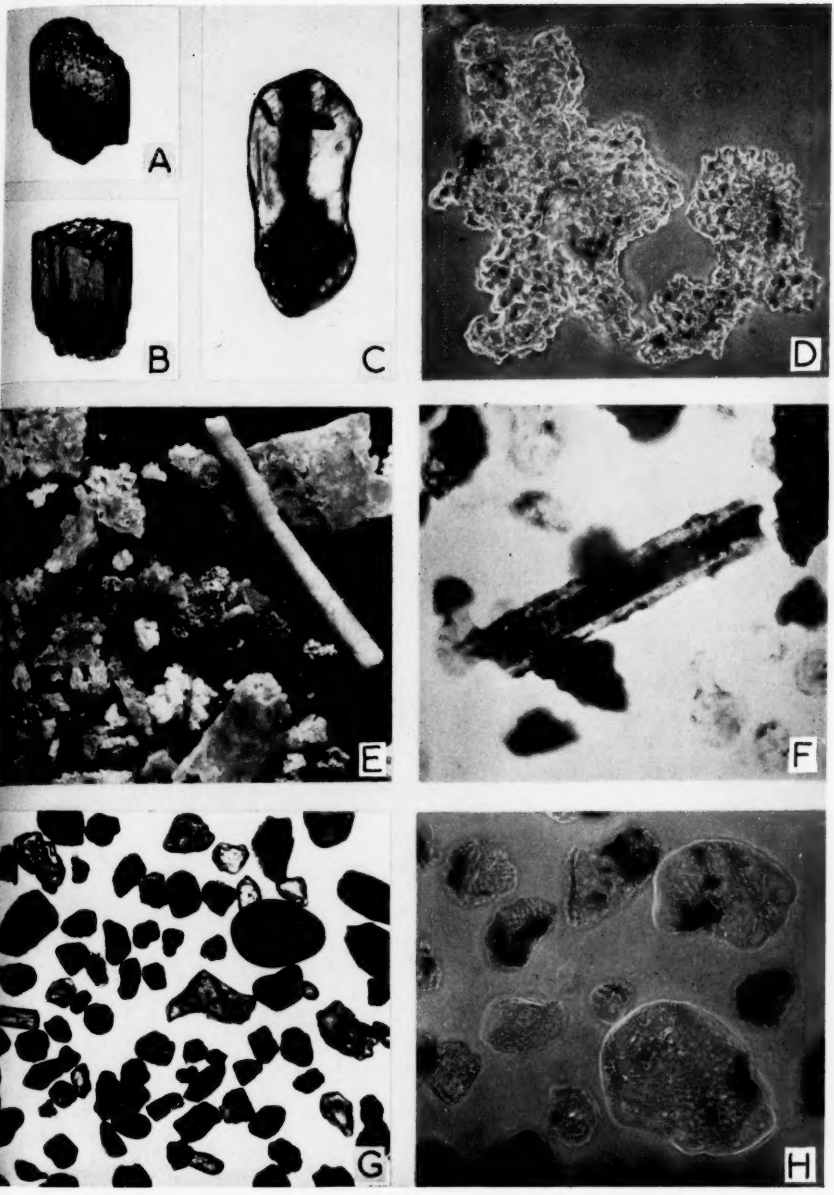


Minerals from glacial deposits and from soils related to igneous rocks (Key p. 209)

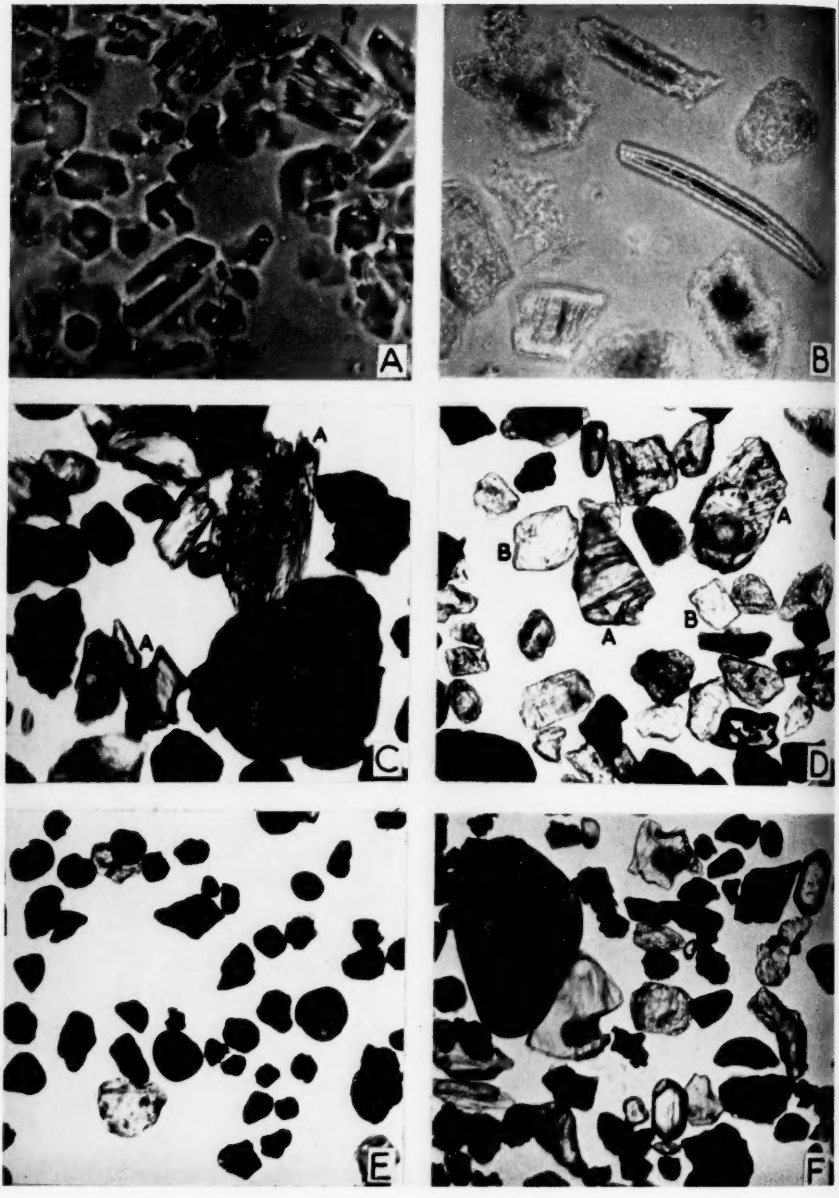
F. SMITHSON—PLATE I



Minerals from soils related to Ordovician, Silurian, and Devonian sediments (Key p. 209)



Minerals from Lower Carboniferous sediments and related soils (Key p. 210)



Minerals from Upper Carboniferous and Triassic sediments and related soils (Key p. 210)

F. SMITHSON—PLATE IV

A PETROGRAPHIC STUDY OF A TROPICAL BLACK EARTH AND GREY EARTH FROM THE GOLD COAST

I. STEPHEN

(Rothamsted Experimental Station, Harpenden)

Introduction

THE crystalline rocks of the Archaean Complex of the Gold Coast can be divided into two groups, one of acidic, the other of basic composition. In the region near Accra the basic rocks form a narrow belt of country extending inwards from the vicinity of Kpone on the coast to the Accra–Ada road, north of which the outcrop widens considerably. The rocks consist of gneiss, granulite, schist, and eclogite, generally rich in hornblende and often containing garnet and pyroxene. This belt is flanked by foliated rocks of acid types, including mica-schist and gneiss, quartzite and quartz-schist.

The Archaean rocks are covered only by short (about 2 to 3 ft.) grassland, with shrubs on termite mounds. The climate is characterized by a relatively low and erratic rainfall with comparatively high humidity. The mean annual rainfall is between 25 and 30 in., more than one-half of which falls during the months of April, May, and June. The mean annual temperature is about 80° F. with little variation throughout the year.

A note on the soils of the area has been given by Junner and Bates of the Gold Coast Geological Survey (1945), who state that:

> Under the climatic conditions obtaining here the basic crystalline rocks undergo slow chemical weathering with the production of black clay and various soluble salts. The climate is sufficiently arid to lead to a concentration of nodular calcium carbonate in the clay. This overburden of calcareous clay is everywhere very thin, averaging only 3 feet on the plains, and very rarely exceeding 7 feet in the valley bottoms. . . . The bedrock shows little sign of decomposition below the top few feet. . . . The acidic rocks on decomposition produce a more sandy overburden, which is generally slightly thicker than that on the basic rocks. On the slopes much of the clay and lime has usually been washed out of the subsoil, but in the valleys the overburden is commonly a calcareous sandy clay. The bedrock is decomposed or partly decomposed to a greater depth, particularly in areas of biotite-quartz-felspar schist, the depth of partial disintegration reaching more than 20 feet in places.

In the present paper an account is given of the mineralogical changes which occur during soil formation from feldspar-quartz-schist and hornblende-garnet-gneiss.

Profile Data

The schist is a light-buff coloured finely banded rock composed essentially of feldspars and quartz, the former minerals being slightly greater in amount. Albite is the dominant feldspar, with subsidiary microcline and orthoclase, the total feldspar approximating to $Ab_{65}Or_{35}$ in composition. Accessory minerals include sericite, as small colourless

scales disseminated throughout the rock, biotite in flakes rarely exceeding 0·2 mm. in size, and finely granular epidote, the two latter minerals being particularly developed along the planes of schistosity.

Profile 1

Position: Mile 32, Accra–Ada road.
Site: Upper slope.
Vegetation: Short grass, mainly *Vetiveria* sp.
Topography: Very gently undulating.
Depth:

0–1 in. Brownish-grey medium-grained sand; loose; single-grain structure.
1–12 in. Pale brownish-grey medium sand; loose; single-grain structure.
12–20 in. Dark brownish-grey gritty sandy clay; rusty mottling and small pisolitic iron and iron-manganese concretions; very compact; cubic structure (½ to 1 in. side); sharp fall in number of grass roots at the top of this horizon.
20–40 in. Yellowish greyish-brown gritty sandy clay; very compact, but less than horizon above; rusty mottling and a few small iron and iron-manganese concretions.
40–48 in. Decomposing gravel from a quartz vein (such veins are very frequent).
48–60 in. Decomposing schist, inclined at about 45°.

The gneiss is a coarsely crystalline rock composed of a brown-green hornblende that occurs as irregular plates and prisms elongated parallel to the banding, and coarse almandine garnet, with accessory pale-green pyroxene, epidote, magnetite, and apatite. Subordinate light-coloured feldspathic bands are common. The feldspar is oligoclase-andesine, and is commonly associated with minor amounts of quartz and garnet.

Profile 2

Position: Mile 29, Accra–Ada road.
Site: Upper slope.
Vegetation: Short grasses, mainly *Vetiveria* sp.
Topography: Very gently undulating.
Depth:

0–6 in. Very dark brownish-grey sandy clay, containing a few small rounded iron and iron-manganese pisolites, and a few small nodules of calcium carbonate; small crumb structure when dry, very plastic when wet; abundant grass roots.
6–24 in. Very dark brownish-grey sandy clay, containing scattered calcium carbonate nodules and a few iron and iron-manganese pisolites; cubic structure (about 1 in. side); very compact when dry and compact when moist; much less root development than in horizon above.
24–36 in. Dark brownish-grey sandy clay, containing abundant greyish white nodules of calcium carbonate, in places forming nodular masses, and a few iron and iron-manganese pisolites; compact, but less so than horizon above.
36–48 in. Decomposing gneiss.

Note: The bands of gneiss and schist are sharply inclined, and vary in their ease of weathering. The more resistant bands give rise to shallower soils, while the weaker bands weather to a greater depth. The horizon depths vary considerably over distances of a few yards.

Analytical data of the soils are shown in Table 1.

The soil derived from the hornblende-garnet-gneiss has the characteristics of a typical tropical black earth, variously called Regur, Black

TABLE 1

Analytical Data

PROFILE 1

	Depth in inches				
	0–1	*1–12*	*12–20*	*20–40*	*40–48*
pH	7·0	6·2	6·4	6·4	6·4
Coarse sand, %	32·7	35·3	25·3	27·6	39·2
Fine sand, %	57·4	57·5	41·8	41·8	34·4
Silt, %	2·8	1·5	2·9	3·8	3·7
Clay, %	8·0	7·5	29·7	27·9	21·8
$CaCO_3$, %	nil	nil	nil	nil	0·2
Exchangeable cations (m.e./100 g.)					
Ca	2·82	1·24	5·57	6·50	5·51
Mg	1·12	0·78	3·81	4·84	1·93
K	0·06	0·06	0·11	0·11	0·07
Na	0·94	0·36	2·60	5·40	5·50
Mn	0·03	0·02	0·01	0·01	0·01
Sr.	0·01	0·01	0·03	0·04	0·02
C/N ratio	8·4	8·1	8·9	4·8	n.d.

PROFILE 2

	Depth in inches		
	0–6	*6–24*	*24–36*
pH	7·5	8·4	7·8
Coarse sand, %	24·4	20·9	21·3
Fine sand, %	32·2	33·7	33·4
Silt, %	10·5	12·3	9·2
Clay, %	30·7	33·1	30·0
$CaCO_3$, %	0·4	0·7	5·5
Exchangeable cations (m.e./100 g.)			
Ca	21·05	15·65	25·40
Mg	0·80	12·32	10·79
K	0·13	0·10	0·10
Na	1·15	6·93	11·89
Mn	0·01	0·005	0·005
Sr	0·08	0·10	0·09
C/N ratio	10·2	9·2	6·7

Note: Determinations of water-soluble salts show that the Na is present almost exclusively in the water-soluble state. The dominant associated anion is Cl'.

Cotton Soil, Tirs, &c., in different parts of the world.[1] Several writers who have reported on these tropical black clays mention associated grey clays containing less calcium carbonate. The grey clays do not seem to be given any special names, but they should probably be placed in a separate great soil group.

[1] A recent review of these soils has been given by H. Oakes and J. Thorpe: Proc. Soil Sci. Soc. Amer. (1951), **15**, 347–54.

The loose sand of the first two layers of Profile 1 is probably derived from the rock below, the clay having been illuviated or translocated laterally. It is a general feature of the middle and upper slope soils developed over rocks of granitic character.

The presence of appreciable amounts of water-soluble Na in the soils is of interest. The dominance of Cl′ as the associated anion suggests that some of the NaCl is wind-borne, as the wind blows fairly strongly off the sea for most of the year.

Concretions

Calcium-carbonate concretions are absent in Profile 1 (apart from minor amounts in the lower horizon), but in Profile 2 they are present as dark to medium-grey irregular grains, particularly in the 24–36 in. soil layer, where they are aggregated to form nodular masses.

Two types of dark-coloured concretions can be recognized in both soils, but in amount are always less than 1 per cent. of the sand separates. One variety is lighter, the other heavier than bromoform (sp. gr. = 2·90). The former occurs as irregular to very well rounded soft grains, steel-grey in colour with a submetallic lustre. On X-ray analysis the material gives a dense background scatter on the film and a few weak lines referable to quartz. Treatment with hot dilute hydrochloric acid bleaches the grains and leaves a white soft residue of very finely divided quartz. An analysis of the acid solution shows 17·4 per cent. Fe_2O_3, and 22·2 per cent. Mn as MnO_2. The absence of any lines on the X-ray diagrams referable to iron or manganese oxides suggests that these are present in the amorphous state.

The heavy concretions occur mainly as hard ovoid grains, medium-brown in colour and with a smooth surface. They give the standard goethite X-ray pattern.

Mineralogy of the Fine Sands

Profile 1

Light detritals (*sp. gr.* $< 2{\cdot}90$). Minerals present in the weathered schist are feldspars (albite, microcline, orthoclase), quartz, biotite-vermiculite, sericite, and calcite. Feldspars are approximately equal to the quartz in amount, and are present mainly as subangular cleavage plates with a white porcelain-like appearance, but they are almost completely absent in the soil layers where quartz in clear, colourless, angular to subangular grains forms more than 95 per cent. of the separate in all the layers of the soil (Fig. 1). Flakes of brown mica present in the weathered schist form 3 to 4 per cent. of the separate. They are present as light-brown poorly defined flakes and scales, and show the golden-yellow lustre typical of biotite altering by hydration. This is confirmed by their X-ray diffraction patterns. In contrast to the fresh biotite, which gives a strong sharp basal reflection at 10 kX, aggregate diagrams of the weathered flakes show a considerably broadened basal reflection centred on 10·3 kX, and an additional weak diffuse basal reflection in the region of 13·5 kX, the presence of these higher spacings being due to the interstratification of more highly hydrated (vermiculite-

like) layers with the original biotite (cf. Walker, 1949). Sericite and calcite occur only in accessory amounts in the weathered schist, and like the biotite-vermiculite are absent in the soil layers above 40 in.

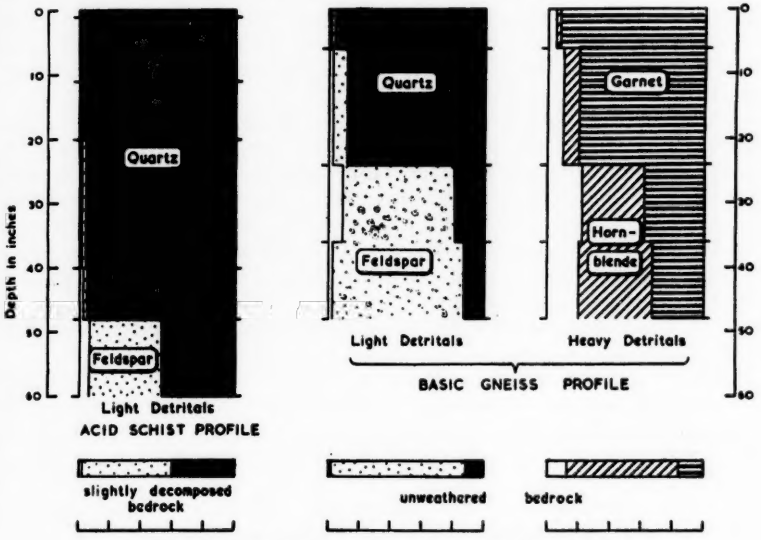


FIG. 1. Distribution of minerals in the fine sands.

Heavy detritals (*sp. gr.* $> 2{\cdot}90$). The amount of heavy minerals is small in all the layers of the profile (< 3 per cent. by weight), the low percentage being due to the characteristically small amounts of ferromagnesian minerals in the parent rock. Members of the epidote-clinozoisite group are 'flood minerals' forming more than 85 per cent. of the separates in all layers from the weathered schist to the surface soil. They occur in characteristic greenish-yellow to colourless subangular grains, the variety clinozoisite showing the anomalous 'ultra-blue' or orange interference colours. As noted in the description of the parent bedrock these minerals are prominent along planes of schistosity and joint planes, to which they give a greenish cast. Their persistence throughout the soil points to their high degree of stability in the zone of weathering. The accompanying minerals include those normally developed in metamorphic rocks of gneissose type, of which staurolite, garnet, goethite, magnetite, zircon, and rutile are the commonest. A few grains of kyanite, tourmaline, green hornblende, apatite, and a blue-green spinel referred to ceylonite are also present.

Profile 2

Light detritals (*sp. gr.* $< 2{\cdot}90$). Minerals present in the separates are quartz, feldspar, and calcite. The weathered gneiss and the 24–36 in. soil layer consist dominantly of feldspar with accessory quartz and

calcite, the latter being concentrated in the soil horizon. The feldspar (oligoclase-andesine) occurs as clear subangular grains, only occasionally showing the characteristic twin lamellae. In the upper two soil layers the elimination of the feldspar by weathering leads to a concentration of quartz, which occurs in clear, subangular to rounded grains, and forms more than 95 per cent. of the separate in the 0–6 in. layer. (Fig. 1.) Calcite is present throughout the profile, but occurs only in accessory amounts in the upper soil layers.

Heavy detritals (*sp. gr.* $> 2{\cdot}90$). All the samples contained an abundance of heavy minerals, ranging from 35 to 45 per cent. by weight of the sands. Minerals present are hornblende, garnet, pyroxene, ore, apatite, and zircon. The dominant feature is the concentration of garnet in the upper (more highly weathered) layers of the profile at the expense of hornblende and other minerals (Fig. 1). In the 0–6 in. layer the garnet forms more than 90 per cent. of the separate. The grains are pink or colourless, usually angular, and often show a distinctive surface patterning. All the grains are perfectly fresh, and appear completely unaffected by weathering.

The hornblende occurs in typical brownish-green cleavage fragments and irregular plates. In amount it approximately equals garnet in the weathered gneiss and the basal soil layer, but is only represented by an occasional grain in the surface soil. Pyroxene forms between 5 and 10 per cent. of the heavy residue below 24 in., but like hornblende is essentially eliminated in the surface soil. It occurs in prismatic to irregular crystals, normally with very frayed terminations. The ore is dominantly magnetite, inherited from the parent bedrock, and subsidiary goethite in the form of small ovoid concretions. Apatite, epidote, and zircon are rare.

Mineralogy of the Clays

Examination of the clay separates ($< 2\,\mu$) from the soils and the weathered rocks was carried out mainly by means of X-ray diffraction, using filtered copper radiation and a 9-cm. powder camera of the type described by MacEwan (1949). In addition, differential thermal records were made of the clay from the weathered rock and the surface soil in each profile. Prior to examination the samples were treated with hot hydrogen peroxide to remove organic matter, and leached with neutral calcium chloride to ensure complete calcium-saturation.

Profile 1

Differential thermal records of the clays (Fig. 2, A and B) show the distinctive intense endothermic reaction at 580–600° C. typical of kaolins, and a moderate endothermic dehydration reaction at about 150° C. The symmetrical nature of the 580–600° C. peak suggests that it corresponds to a well-crystallized kaolin, since with the halloysitic type of clay this peak is markedly asymmetric, with a very steep slope on the recovery side (Bramão, Cady, and Hendricks, 1950). It is probable that the low-temperature dehydration reaction can be entirely ascribed to montmorillonite, and the shoulder on the recovery side of this peak is characteristic of Ca-saturated montmorillonite.

These suggestions are confirmed by X-ray analysis. In all the samples diagrams of glycerol-saturated oriented aggregates show two integral series of basal reflections of 17·7 kX and 7·15 kX periods, corresponding to glycerol-montmorillonite and kaolin respectively. The sharp (001) spacing of 7·15 kX is characteristic of the well-crystallized kaolins, since

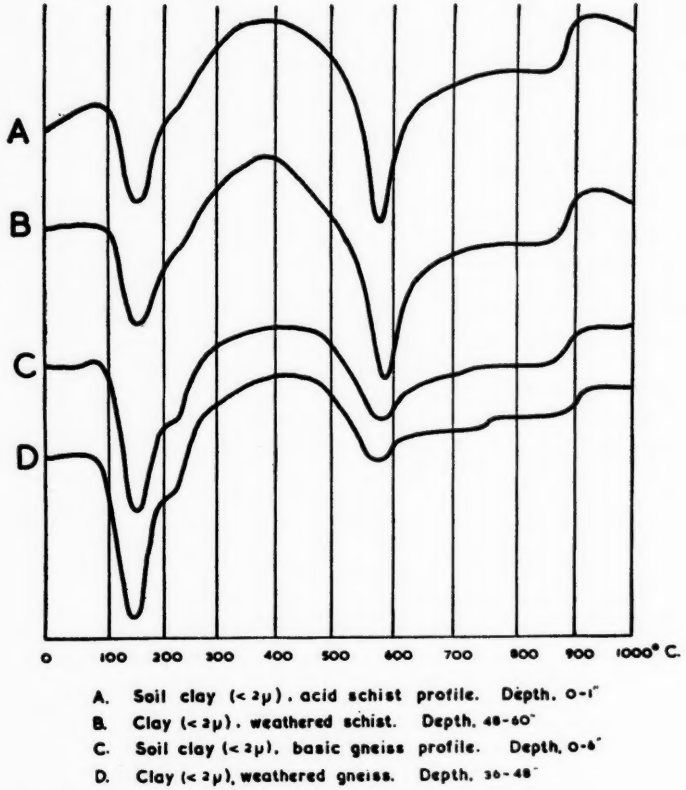


FIG. 2. Differential thermograms of clays.

with halloysite, in addition to the reflection being broadened, the value of this spacing is 7·3 kX or greater. By comparison of the X-ray diagrams with those of mixtures of montmorillonite (an American bentonite) and kaolinite in definite proportions (MacEwan, 1946), the montmorillonite:kaolin ratio is estimated at approximately 3:2 in the weathered schist, decreasing to 1:1 in the surface soil.

Quartz, as shown by the presence of its strong line at 3·35 kX, occurs throughout the profile, increasing from trace amounts in the clay from the weathered schist to a few per cent. in the surface soil.

Profile 2

The thermal curves of the clays are similar in pattern to those from Profile 1, indicating the presence of the same minerals, but the marked differences in intensity of the peaks show they are present in other proportions (Fig. 2, C and D).

On X-ray analysis all the samples show the characteristic sequence of reflections of glycerol-montmorillonite, with spacings of 17·7 kX and an integral series of higher orders. A very weak reflection at 7 kX indicates the presence of a kaolin mineral. The amount of kaolin associated with the montmorillonite is estimated at less than 5 per cent. in the weathered gneiss, but increases to approximately 5 per cent. in the surface soil. Quartz and calcite are present in the clays in trace amounts throughout the profile.

Discussion

Studies of the quantities of the minerals in the sands of the two profiles give interesting information about their relative stabilities. In the basal layers of the soil profiles the general character of the mineral assemblage reflects closely the composition of the parent rock, but with further weathering the resistant species (quartz, garnet) are concentrated and the less resistant species (feldspars, hornblende, and other ferromagnesian minerals) decrease in abundance or disappear completely. This trend of alteration leads, in the upper soil layers, to quartzose sands derived from the feldspar-quartz-schist, and quartz-garnet sands from the hornblende-garnet-gneiss.

The nature of the parent bedrock in affecting the composition of the colloidal fractions of the soils is also shown by this study. The clays from the basic gneiss profile consist almost exclusively of montmorillonite, but in the acid schist profile montmorillonite and kaolin occur in approximately equal amounts.

Laboratory experiments on the hydrothermal synthesis of clay minerals (Noll, 1936) and the study of field occurrences suggest that the formation of clays of the montmorillonite type is promoted by alkaline conditions, when there is a sufficient supply of magnesium or ferrous and ferric iron, to combine with the silica and alumina. Under the rather arid conditions of this coastal section of the Gold Coast, the weathering of the basic gneiss with the simultaneous alteration of hornblende and pyroxene (releasing Mg, Fe, Ca) and the feldspar (the main source of Si, Al) provides ideal conditions for the production of essentially monomineralic montmorillonite clays.

The presence of appreciable quantities of montmorillonite in the soils derived from the acid schist is perhaps surprising, as the feldspars which, together with quartz, form the bulk of the rock, are deficient in the bases Mg, Fe, and Ca, and consequently are not favourable sources for the formation of montmorillonite. The presence of mixed layer biotite-vermiculite minerals in the weathered schist suggests that the biotite is probably the main source of the required bases, as studies of the chemical changes which occur on weathering during the conversion of biotite to vermiculite (Denison, Fry, and Gile, 1929: Walker, 1949) show that

magnesium and other bases tend to be lost from the crystal lattice as weathering proceeds. It appears that the climate is sufficiently arid to ensure that the liberated bases are retained in the weathering system, thus raising the pH initially above 7, and promoting montmorillonite formation. Since the amount of these bases is limited the remainder of the Si and Al goes to form kaolin.

Summary

A comparative study of two profiles derived from feldspar-quartz-schist and hornblende-garnet-gneiss of the Archaean Complex near Accra, Gold Coast, has been made. The basic gneiss weathers to give a sandy clay soil characterized mineralogically by quartz-garnet sand and montmorillonitic clay. The acid schists gives a quartzose sandy soil with smaller amounts of clay comprising both kaolin and montmorillonite.

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THE OCCURRENCE OF LEPIDOCROCITE IN SOME BRITISH SOILS

WITH ONE PLATE

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Introduction

THE orange or ochreous spotting or blotching often found in gleyed soils has been attributed to ferric oxide, and Bloomfield (1951) has shown that in Rothamsted subsoil the iron content of the grey zone is considerably less than that of the associated orange-coloured zone.

In the course of a survey of the clay minerals of some Lancashire soils lepidocrocite has been recognized in a number of clay fractions. Lepidocrocite, γ-$Fe_2O_3.H_2O$, is orthohombic with $a_0 = 3{\cdot}87$ Å, $b_0 = 12{\cdot}51$ Å, and $c_0 = 3{\cdot}06$ Å (Ewing, 1935). The crystal habit according to Dana (4th edition) is flaky, elongated perpendicular to the *b*-axis. The strongest line of the powder diffraction pattern occurs at a spacing of 6·25 Å and represents the (020) reflection. When the oriented aggregate method is used, as is generally the case in clay mineral investigations, the (020) reflection is enhanced in intensity in a similar manner to the enhancement of the low order (00*l*) reflections from the clay minerals. In this way the 6·25 Å reflection of lepidocrocite is more readily visible on an aggregate photograph than the reflections of goethite, α-$Fe_2O_3.H_2O$, whose crystals do not show preferred orientation. In many cases in the present study only the 6·25 Å lepidocrocite diffraction was recorded, but in some samples where the concentration of iron oxides was high, lines of both lepidocrocite and goethite were observed. It seems likely that the goethite is associated with lepidocrocite in some of these soils.

This paper presents a preliminary survey of the occurrence of lepidocrocite in some British soils and gives an account of the experiments by which it was identified. It also draws attention to experimental methods which can lead to erroneous results.

Identification of Lepidocrocite in Soils

Identification in most cases had been on the basis of a single line at 6·25 Å. This, the strongest lepidocrocite line, is the only one which can be observed when the mineral is present in small amounts. The strongest line of the structurally similar boehmite, γ-$Al_2O_3.H_2O$, occurs at a spacing of 6·23 Å, and on our cameras these lines would not be resolved. It has also been found that calcium oxalate trihydrate can be formed by the peroxidation of the surface layers of some soils, and this material, with its strongest line at 6·13 Å, could also be confused with lepidocrocite.

Lepidocrocite and boehmite can be differentiated by their reactions on heating. A soil clay (La 26/4), which was thought to contain lepidocrocite on the basis of the 6·25Å line, was heated in the same furnace as a sample of finely powdered boehmite for 12 hours at 270° C. Diffraction patterns showed that while the boehmite pattern persisted after this

treatment, the 6·25 Å line in the soil clay pattern had disappeared, showing that lepidocrocite rather than boehmite was present in the soil.

It has been observed that the peroxidation of many surface soils from the north and west of England could have given rise to erroneous results unless special care had been taken.

An example is the surface layer of a soil from New House Farm, Wheelton, Lancashire, which was used for some of the experiments described in this section. This soil belongs to the *Gratrix* series and the surface layer is a brownish dark grey (10 YR 2/1·5) peaty loam, very high in intimate and mechanical organic matter. Analytical figures show 17·2 per cent. organic carbon and 0·5 per cent. organic nitrogen with a loss on ignition of 26·2 per cent.

The clay for the experiments described in this section was separated by dispersion with Calgon, flocculated with calcium chloride, washed free of electrolyte with water, and then peroxidized with 40 vol. hydrogen peroxide. An X-ray diffraction pattern of the clay after peroxidation showed the lines given in Table I which were not present on a pattern of unperoxidized clay. For conciseness these lines will be known as the 'extra' lines.

TABLE I

Peroxidized soil clay		*Calcium oxalate trihydrate after Lecompte, Pobeguin, and Wyart (1943)*	
Spacing	*Intensity*	*Spacing*	*Intensity*
6·2 Å	Medium strong	6·13 Å	Strong
3·92 Å	Very weak	..	..
3·075 Å	Very weak	3·07 Å	Medium
2·76 Å	Medium strong	2·76 Å	Very strong

These reflections, except for the weak line at 3·92 Å, compare well with those given by Lecompte, Pobeguin, and Wyart (1943) for the trihydrate of calcium oxalate prepared by precipitation from dilute solutions.

According to Sandell and Kolthoff (1933), calcium oxalate trihydrate is precipitated at room temperature, but the transformation from the trihydrate to the monohydrate takes place on standing in the mother liquor for a day or longer at room temperature and much more rapidly at higher temperatures. They also state that the monohydrate is formed if the precipitation is made at higher temperatures.

In the peroxidation of soils it is likely that the oxalic acid is formed by the oxidation of the soil organic matter, and that this oxalic acid precipitates the exchangeable or combined calcium as calcium oxalate. As the peroxidation is carried out in hot suspensions it would be expected that the monohydrate would be precipitated.

Experiments showed that precipitation in the cold from dilute solutions, with the rapid removal of the mother liquor, gave a mixture of monohydrate and trihydrate in which the trihydrate predominated. Allowing the precipitate to stand in contact with the mother liquor or heating the precipitate in the mother liquor changed the trihydrate to the monohydrate. Identical precipitations from dilute solutions, one in

the presence of 40 vol. A.R. hydrogen peroxide, the other without peroxide, showed a much greater proportion of trihydrate in the precipitate made with peroxide although both were mixtures. Further, boiling the precipitate made in the presence of peroxide, not in the mother liquor but in water, increased the crystal size of the trihydrate but did not markedly alter the proportion of trihydrate to monohydrate. These experiments suggested that the trihydrate had been stabilized by the peroxide or an impurity.

A further piece of evidence in favour of the identification of the material causing the 'extra lines' as calcium oxalate trihydrate was the fact that clay separated in an identical way, but flocculated with sodium chloride instead of calcium chloride and then peroxidized, did not give any of the 'extra lines'.

In order to differentiate calcium oxalate trihydrate and lepidocrocite, both of which have their strongest lines close to 6·2 Å, heating experiments were carried out in the hope that one would be more stable to heat than the other. It was found that lepidocrocite could be heated to at least 180° C. for 12 hours without any change in the X-ray diffraction pattern taking place. Synthetic calcium oxalate trihydrate, on the other hand, altered to the monohydrate with a strong line at 5·9 Å when heated at 150° C. for 12 hours. By heating the trihydrate at 180° C. for 12 hours an amorphous product was obtained. Similar experiments with the soil oxidation product showed it to be identical in this respect to the trihydrate, whereas heating a soil clay which had been recognized to contain lepidocrocite at 180° C. for 12 hours had no effect on its diffraction pattern.

The 3·92 Å line on the X-ray diffraction pattern obtained with peroxidized soil clay has been obtained in some synthetic preparations of calcium oxalate, but as these were always mixtures it was not possible to assign it to any particular hydrate. According to the data of Lecompte, Pobeguin, and Wyart (1943) it could be the strongest line of anhydrous calcium oxalate. It is almost certain that in the peroxidized soil clay it is associated with calcium oxalate as in some peroxidized clay all the 'extra lines' including that at 3·92 Å are spotty, denoting large crystals, whereas the clay lines are smooth.

The foregoing observations suggest that soil clays should not be peroxidized before taking X-ray diffraction patterns. If they are peroxidized, the clay should be saturated with an ion such as sodium or potassium which gives a soluble oxalate.

The Occurrence of Lepidocrocite in Soils

Lepidocrocite was first observed in the clay from *Rothwell* silty clay loam (La 25) from Bradley Wood, Rivington, Lancashire (for all profile descriptions see Appendix). The recognition was not unambiguous as only a small proportion of the mineral was present in the clay, so only the strongest line at 6·25 Å could be seen. However, circumstantial evidence in the form of colour correlation suggested that the mineral was lepidocrocite. Table 2 shows how the occurrence of the 6·25 Å line is related to the colour of the soil (La 25).

Plate I, A–D show oriented aggregate photographs, taken with CoKα radiation, of the clay from successive horizons of this profile, I, A being the surface layer.

TABLE 2

Depth	*Colour of soil*	*Indications of lepidocrocite*			
		Aggregate photograph		*Powder photograph*	
		Spacing	*Intensity*	*Spacing*	*Intensity*
0–8 in.	Greyish-brown (10 YR 5/3)	..	..	..	..
8–15 in.	Orange-yellow	6·25 Å	Medium	6·25 Å	Weak
15–24 in.	Dull grey with much orange mottling	6·25 Å	Medium strong	6·25 Å	Medium
24 in.+	Dull grey (10 YR 5·5/1) with greyish-brown and a little orange blotching	6·25 Å	Very weak	..	..

These results suggested that the lepidocrocite is of pedological origin since the mineral was almost entirely absent from the lowest horizon.

The pattern recorded in Table 2 is repeated in the adjacent and similar *Hallsworth* silty clay loam, i.e. the appearance of orange blotching is paralleled by the appearance of the 6·25 Å lepidocrocite line on the oriented aggregate pattern of the soil clay. In this case, lepidocrocite occurred in the lowest horizon in similar amounts to the two horizons above it in the profile. This suggests that the profile pit had not reached the soil parent material, but as both *Rothwell* and *Hallsworth* soils are derived from Millstone Grit shales it might seem that the lepidocrocite was of geological rather than pedological significance. However, a sample of Millstone Grit shale from an adjacent locality, viz. Moses Cocker's Farm, Rivington, Lancashire, gave no indications of lepidocrocite, although the clay minerals proper appeared to be similar to those in the lowest horizons of *Rothwell* and *Hallsworth* soils.

Furthermore, examination of five soils from Anglesey derived from different parent materials also showed the presence of a 6·25 Å line where orange colours predominated. Table 3 gives a brief summary of the results of X-ray examination of these soil clays.

The results in Table 3, which showed that soils on a variety of parent materials contained lepidocrocite, were further evidence that the lepidocrocite was of pedological origin.

One sample has become available in which it was possible to hand-pick the differently coloured segregations. This was horizon 3 of a *Gratrix* soil from Anglezarke Moor, Lancashire (Appendix). The rusty pipes were separated from the surrounding grey material and diffraction patterns were made of the clay fraction of each. Plate I, E and F show these patterns taken under identical conditions with CoKα radiation. The rusty material shows, in addition to weak clay mineral reflections, the patterns of lepidocrocite and goethite. The grey material gave only the patterns of clay minerals. In the pattern from the rusty material all

the strong lines of lepidocrocite are present along with the strongest goethite line. This evidence, in conjunction with what has been given previously, makes fairly positive the identification of the material giving the 6·25 Å line in these soil clays as lepidocrocite.

TABLE 3

Soil, Series Name	*Depth*	*Colour*	*Indications of lepidocrocite on aggregate photograph*	*Parent material*
A 8 *Frogmoor*	12–20 in.	Very heterogeneous, brown, yellow, and orange mottle	Weak 6·25 Å line	Drift from Old Red Sandstone and Carboniferous Basement conglomerate
A 10 *Pentir*	8–14 in.	Yellowish-brown blotched with pale brown	Weak 6·25 Å line	Sandy boulder clay of Carboniferous Sandstone conglomerate
	14–22 in.	Yellowish-brown as above, pale areas larger	Medium 6·25 Å line	
A 11 *Eifion*	7–14 in.	Light brown grey (2·5 YR 6/2) with orange mottle	Medium 6·25 Å line	Drift from Coedana Granite
A 13 *Nerquis*	14–21 in.	No uniform colour, orange mottle on grey brown	Medium to weak 6·25 Å line	Drift from Millstone Grit shales
	21–28 in.		Medium 6·25 Å line	
A 15 *Cegin*	20 in.+	Principally yellow with grey mottle	Medium 6·25 Å line	Drift from Ordovician shales

It should be noted that the soils in which this mineral has been reported are those which are not freely drained. No evidence has been obtained for the presence of lepidocrocite in the clays from well-drained soils in Anglesey, but a more extensive study of the relation of drainage to occurrence of lepidocrocite is required.

Recommended Methods of X-ray Diffraction Work on Soil Clays

These have been evolved during the course of the present work and the lessons learnt have been incorporated. The method of investigation was by X-ray diffraction examination of the clay fraction of the soils for which the oriented aggregate technique was mainly used, as it is the best method for identifying the clay minerals. This technique has been described by Nagelschmidt (1941).

The clays were separated by dispersing sufficient soil to give a 1 per cent. suspension of clay in a high-speed stirrer for 1 hour in a 0·1 per cent. (w/v) solution of Calgon (sodium hexametaphosphate). A 5-c.c. pipette sample, taken at 10 cm. depth after settling for 16 hours at 20° C., gives sufficient clay of e.s.d. $< 1{\cdot}4\,\mu$ for all the necessary examinations. It has been found that Calgon disperses the clay in most soils

without recourse to any other treatment. Enough of this suspension, about 1 c.c. on my apparatus, was centrifuged in a Perspex centrifuge tube on to a glass plate in the base to give an aggregate about 0·1 mm. thick. Only 10 minutes is required to make an aggregate by this method, and it is thus very much quicker and easier than the settling method. These aggregates seem to have better preferred orientation and greater cohesion and hence are easier to handle than those prepared by settling. For powder photographs part of the pipette sample is centrifuged in the ordinary way and the powdered clay is mounted in tubes made of Durofix. The method does not involve any pre-treatment of the soil or the clay except that required for dispersion.

It seems to have become common practice to pre-treat clays to remove organic matter and amorphous material as a matter of course before taking X-ray diffraction patterns, and as shown above this may lead to erroneous results as, for example, calcium oxalate can be formed by peroxidation unless precautions are taken. In some cases it may be necessary to pre-treat a soil clay to obtain a clear diffraction pattern, but in my experience no case has arisen where pre-treatment was necessary. It is felt that in the past much valuable information has been lost through the indiscriminate cleaning of clays.

Summary

Lepidocrocite of pedological origin occurs in the gleyed soils of the north and west and it has also been found that calcium oxalate trihydrate can be formed by the peroxidation of the upper layers of some soils. As the strongest reflection of calcium oxalate trihydrate, of lepidocrocite, and of boehmite occurs at about 6·25 Å, the appearance of this line could lead to the misinterpretation of X-ray photographs, especially if the materials were present in small amounts. A method of differentiating calcium oxalate trihydrate, lepidocrocite, and boehmite by heat treatment is given. It was found that calcium oxalate trihydrate gave an amorphous product on heating to 180° C. for 12 hours, while lepidocrocite and boehmite were unaffected. Heating to 270° C. for 12 hours does not affect boehmite, whereas lepidocrocite is converted to haematite. Evidence is presented which suggests that lepidocrocite is the pigment responsible for the orange mottling which often occurs in soils which are not freely drained. Finally, a rapid and effective method of preparing soils for X-ray diffraction studies is given.

Acknowledgement

I wish to express my thanks to Dr. A. Muir for discussion and continued interest in this work.

APPENDIX

This Appendix gives the full profile descriptions of some of the soils used in these investigations. For those from Lancashire I am indebted to Mr. E. Crompton and for those from Anglesey to Mr. J. Harrop, both of the Soil Survey of England and Wales.

Profile Descriptions

La 25. Series: Rothwell (silty clay loam). *Locality*: Bradley Wood, Rivington, Lancs. *Major group*: Meadow soil. *Drainage of profile*: Imperfect (almost free). *Drainage of site*: Excessive. *Parent material*: Boulder Clay derived almost entirely from Millstone Grit Shales. *Vegetation*: Permanent pasture—*Festuca, Agrostis, Holcus, Galium*, &c.

Profile

0–8 in. Greyish-brown (10 YR 5/3) silty clay loam; cloddy, fissured, and very fine porous; friable, abundant intimate and mechanical organic matter, abundant roots; air dry; ants on surface, earthworms throughout profile. Merging boundary.

8–15 in. Orange-yellow silty clay; slightly stony, stones subangular and up to 2 in. in diameter; loose cloddy with a tendency to crumb, more porous and less fissured than top horizon; friable, organic matter concentrated about root channels; a few roots; just moist. Merging boundary.

15–24 in. Dull grey with much organic blotching silty clay; a few stones, columnar, fissured, plastic to tenacious when wet; a few roots; just moist. Merging boundary.

24 in. Dull grey (10 YR 5·5/1) with greyish-brown and a little dull orange blotching clay silt; a very few stones; columnar, fissured, plastic; a very few roots; just moist. Probably shales immediately below.

La 31. Series: Gratrix. *Locality*: Anglezarke Moor, Lancashire. *Major group*: Peaty gley. *Drainage of profile*: Very poor. *Drainage of site*: Fairly satisfactory. *Parent material*: Glacial till composed of Carboniferous sandstones and shales. *Vegetation*: *Eriophorum vaginatum* with some *Deschampsia flexuosa*.

Profile

4–0 in. Very dark brown, nearly amorphous, slightly greasy peat. Clearly defined boundary.

0–8 in. Dull brownish-grey (5 YR 4/2) with darker organic remains of old roots light to medium clay with some sand grains; broad prismatic structures with dark coating of organic matter on structure faces.

8–18 in. Dull lightish grey (10 YR 5/2) with orange deposition along some old root channels (5 YR 5/8), clay; rather weaker prismatic structures with dark coating of organic matter on structure faces. Merging boundary.

18–34 in. Pale grey (5 YR 6/1) with orange root channels (5 YR 5/8), heavy clay or silt clay; weaker prismatic but bright orange staining on structure faces. Merging boundary.

34 in.+ Olive grey-green (5 YR 4/2) with some blue-grey (2·5 Y 4·5/0) with reddish-orange on old root channels and around some stones (3·5 YR 5/8). Much soft rotting shale giving a somewhat laminated structure.

A 8. Series: Frogmoor. *Locality*: 400 yards SE. of Erddreiniog Farm, Tregaian, Anglesey. *Major group*: Gley (surface water). *Drainage of profile*: Impeded. *Drainage of site*: Moderate–poor. *Parent material*: Drift of predominantly O.R.S. material with admixture of Carboniferous Basement conglomerate and schist. *Vegetation*: Old ley—good condition, ryegrass and meadow grasses with clover.

Profile

0–4 in. Greyish-brown, occasional rusty staining round root channels, light loam to medium loam; fine cloddy, porous, moderately friable; much intimate and mechanical organic matter, abundant roots, wet; earthworms present. Merging boundary.

4–12 in. Brown (7·5 YR 5/4) with orange mottle, light loam to medium loam, cloddy finely porous, compact, only slightly tenacious; mainly intimate humus, some mechanical organic matter; roots fewer than above and many dead; wet; earthworms present. Fairly sharp boundary.

12–20 in. Colour very heterogeneous, brown yellow and orange mottle; heavy loam, cloddy, compact and tenacious; very little organic matter; a few roots; wet; occasional worm tracks.

20–28 in. Generally yellow-brown with streaks and mottling of reddish (O.R.S.) material and much micaceous material; heavy loam; massive, compact and tenacious; traces of mechanical organic matter; root tracks visible; moist to wet; no evidence of earthworms.

A 10. Series: Pentir. *Locality*: 150 yards east of Cae-brych, Penrhos Lhgwy. *Major group*: Podzolic Gley. *Drainage of profile*: Impeded. *Drainage of site*: Very poor. *Parent material*: Sandy Boulder Clay—Carboniferous Basement Conglomerate. *Vegetation*: *Erica tetralix*, *Molinia*, &c.

Profile

0–3 in. Very dark brown fibrous peat, spongy, porous, waterlogged. Sharp boundary.

3–8 in. Dark brown, grading to yellowish-brown at base, peaty loam; suggestion of lamination; finely porous, compact; some mechanical organic matter; erica roots; waterlogged. Very sharp boundary.

8–14 in. Yellowish-brown blotched with pale brown fine loamy sand; slightly prismatic or columnar; compact; old root channels, a few dead roots; wet.

14–22 in. Yellowish-brown; pale areas larger, loamy sand; numerous stones of Carboniferous Basement conglomerate; no well-defined structure; very slightly fissured; compact and tenacious; wet.

A 11. Series: Eifion. *Locality*: 250 yards north of Caer-ycht, Ceirchiog. *Major group*: Gley (surface water). *Drainage of profile*: Impeded. *Drainage of site*: Poor, water standing at surface. *Parent material*: Drift from Coedana Granite. *Vegetation*: Rushes, mosses abundant.

Profile

0–7 in. Dark grey-brown (10 YR 4/2) with rusty staining along root channels; light loam, nutty, porous, friable; much intimate and mechanical organic matter, abundant roots in surface 2 in.; waterlogged; earthworms present. Sharp boundary.

7–14 in. Light brown-grey (2·5 YR 6/2) with orange mottle; sandy light loam, angular fragments suggestive of pyramidal structure; porous and fissured; mainly mechanical organic matter, few roots. Merging boundary.

14–22 in. Similar to above, larger grey areas down prisms, sandy medium loam, few stones; prismatic, fissured, compact; wet. Merging boundary.

22–28 in. Blotched grey and orange, medium loamy sand; few stones, compact and only slightly tenacious; wet.

A 13. Series: Nerquis. *Locality*: 200 yards west of Pen Crug Mawr, Llangristiolus. *Major group*: Gley (ground water). *Drainage of profile*: Imperfect. *Drainage of site*: Moderately good. *Parent material*: Drift from Millstone Grit and associated shales. *Vegetation*. Recent.

Profile

0–7 in. Very dark grey-brown (10 YR 3/2) light loam; few stones, chiefly Millstone Grit; cloddy, porous, friable; large amounts of intimate humus, abundant healthy roots; moist; earthworms present. Merging boundary.

7–14 in. Dark grey (10 YR 4/2) light loam; few stones, chiefly Millstone Grit; large clods, porous, friable; roots present; moist to wet. Sharp boundary.

14–21 in. No uniform colours, orange mottle on grey-brown, manganese dioxide streaks and lumps; approximately 7·5 YR 5/4 and mottle; medium to heavy loam; occasional large stones of grit and some Mona Complex rocks; faintly prismatic, slightly fissured, compact and fairly tenacious, dead roots and remains only; abundant large roughly spherical manganese dioxide cemented lumps; moist. Merging boundary.

21–28 in. Colour and concretions as above; medium to heavy loam, slightly fissured; moist.

A 15. Series: Cegin. *Locality*: ½ mile north of Chwaen goch Farm. *Major group*: Gley (surface water). *Drainage of profile*: Impeded. *Drainage of site*: Very poor. *Parent material*: Drift from Ordovician shale. *Vegetation*: Rushes and grasses.

Profile

0–11 in. Brownish-grey with brown mottling and streaks along root channels, heavy silty loam; very few small stones; tendency to prismatic structure, slightly porous and fissured; much mechanical organic matter, coarse fibrous mat at surface, frequent roots below mat; no earthworms; wet. Sharp boundary.

11–13 in. Dark brown peaty medium loam, cloddy, porous, few roots; wet; sharp boundary.

13–20 in. Grey with some yellow mottle, heavy silty loam; slightly prismatic, only slightly porous, fairly tenacious; dead roots only; wet. Merging boundary.

20 in.+ Principally yellow with grey mottle, heavy silty loam; very little structure, breaks up evenly, impervious, tenacious and compact; roots almost absent. Wet.

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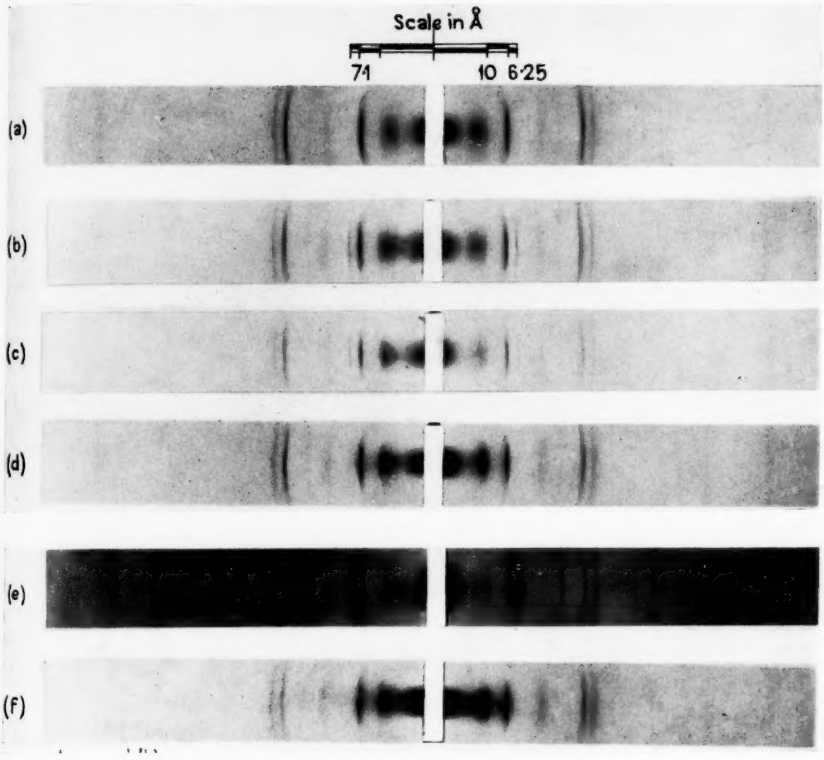

G. BROWN—LEPIDOCROCITE

PLATE I (*a*) Air-dry oriented aggregate photograph of clay fraction of surface horizon of *Rothwell* silty clay loam.

(*b*), (*c*), and (*d*) are similar photographs of the successive horizons down the soil profile.

(*e*) Air-dry oriented aggregate photograph of the clay fraction of rusty separate from horizon 3 of *Gratrix* soil.

(*f*) Similar photograph of grey separate from same horizon.

All photographs were taken with CoKα radiation.

A SEMI-MICRO METHOD FOR THE PREPARATION OF SOIL CLAYS FOR X-RAY DIFFRACTION STUDIES

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Introduction

PREVIOUS studies in soil clay mineralogy have dealt mainly with the clay mineral content in different horizons of the soil profile. Recent work by the writer (Brown, 1953) suggests that soil genesis could be understood better by relating soil morphology and mineralogy more closely. For example, in gley soils the difference in mineral composition between the rusty mottles and their greyish surroundings is obviously connected with the mode of formation of these soils. A rapid method has been devised for the preparation for X-ray examination of the clay fraction from small amounts of soil. The method will enable the clay from separate small morphological features to be examined.

Method

Many methods for clay separation advise pretreatment of the soil such as washing with dilute acid and boiling with hydrogen peroxide. These should not be used unless the soil will not disperse without them as they may affect the clay.

Two different processes can be used to separate the clay fraction of soils.

1. Complete removal of the clay fraction by repeated dispersion, sedimentation, and decantation.
2. Dispersion and sedimentation and the removal of a pipette sample at the appropriate depth for the size fraction required.

Process 1 takes a long time. Process 2, previously used (Brown, 1953), needs about 5 g. soil, the exact amount depending on the proportion of clay. The method described in this paper is a modification of process 2 whereby less than 0·1 g. soil can be used for the preparation of clay for X-ray work.

Previously (Brown, 1953) oriented aggregates were made by centrifuging a 1 per cent. suspension of clay on to a removable glass plate in the base of a perspex centrifuge tube. The supernatant liquid was poured off after centrifuging, the glass plate with clay removed, and the clay dried on the glass plates at 40–50° C. This is much quicker and simpler than allowing the suspension to evaporate to dryness in a vacuum desiccator and appears to give stronger, more cohesive aggregates. In addition, any soluble dispersing agent is removed in the supernatant liquid instead of being left with the clay.

A 1 per cent. suspension is best for the preparation of aggregates. Originally enough soil was dispersed in 150 ml. water to give this concentration of clay. Sedimentation was carried out in 100-ml. measuring cylinders which hold 150 ml. when filled. For a soil with 25 per cent.

clay, 6 g. are needed. In the modified micro method enough soil is used to give a 1 per cent. suspension of clay when the soil is dispersed in 1·0 ml. water. For a soil with 25 per cent. clay less than 0·05 g. of soil are needed. The soil is dispersed by shaking for ½–1 hour in water to which enough 5 per cent. Calgon solution at pH 8 has been added to

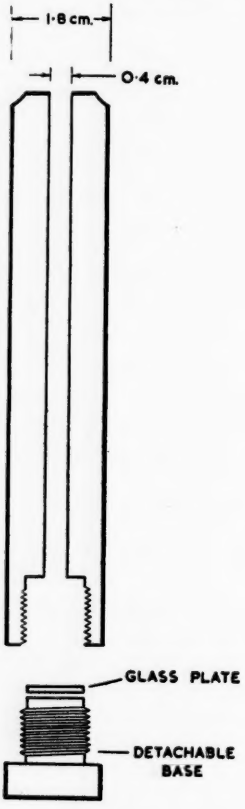

FIG. 1.

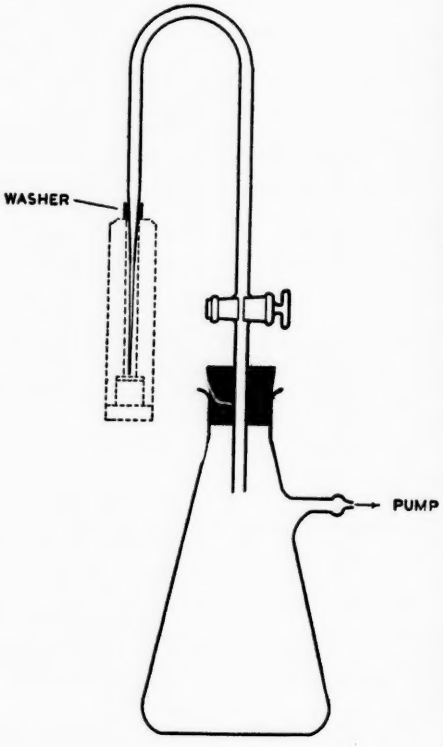

FIG. 2.

give a final concentration of Calgon in the dispersion medium of 0·1 per cent. w/v. It has not been found necessary yet to pretreat a soil in any other way either to disperse the clay or to obtain clear diffraction patterns.

After dispersion, sedimentation is done in specimen tubes 2 cm. high and 0·8 cm. diameter. A pipette with a long narrow jet (about 1-mm. bore) is used to take a sample from 1 cm. depth after standing for 48 minutes at 20° C. This gives clay e.s.d. less than 2 μ (Stokes Law). The sample is transferred directly from the pipette to the centrifuge tube shown in Fig. 1. The size fractionation is not accurate, but no method

is really satisfactory, all being based on settling velocities. If the same time of settling, depth of sampling, and temperature is used samples should be comparable. If a finer fraction is required a longer time of settling can be given, but times become prohibitively long for particles e.s.d. less than 0·05 μ. Cf. Russell (1943).

The large-bore centrifuge tubes used previously (Brown, 1953) gave circular clay aggregates 1·2 cm. in diameter. Much less than this is sufficient for X-ray work, so perspex centrifuge tubes (Fig. 1) have been made with internal diameter 0·4 cm. It was found that 0·1 ml. of a 1 per cent. suspension, i.e. 1 mg. of clay, makes a good aggregate with these tubes. There is enough clay in one of these aggregates for several specimens and also enough for normal powder patterns. Air-locks form in narrow-bore centrifuge tubes when one tries to pour liquid in or out, so the pipette with the long narrow jet which is used to sample the clay from the sedimentation vessel is used to put the clay suspension into the centrifuge tube. A similar pipette, fixed to a stand (Fig. 2), is used to withdraw the supernatant liquid after centrifuging. The perspex centrifuge tube is raised over the jet until its top touches a washer made of cork or rubber which is exactly placed so that the jet of the pipette reaches but does not touch the clay aggregate. When the pipette is completely inserted the tap to the vacuum pump is opened and the supernatant liquid is sucked away. The base of the perspex tube is then unscrewed, the glass plate removed, and the clay dried.

Discussion

The oriented aggregate method (Nagleschmidt, 1941) when used properly is best for the examination of clays. Firstly, the enhancement of the diagnostic (00*l*) reflections allows them to be seen when a mineral is present in small proportions. Secondly, (*hk*) and (*hkl*) reflections are greatly weakened compared to a powder pattern and hence a pattern results which is simpler than the powder pattern. Thirdly, by reducing exposure times for a given intensity of pattern, the intensity of the background relative to the lines is reduced and the pattern is much clearer. For as much information as possible about a clay more than one pattern is needed. Heating the clay, saturation with different cations, and solvation by polar molecules can all change the X-ray pattern and are recommended as diagnostic tests (Bradley, 1945; Walker, 1949). Powder patterns, i.e. patterns of unoriented specimens, in addition to (00*l*) reflections, give the (*hk*) and (*hkl*) lines which are sometimes helpful. The best single test, however, is an oriented aggregate pattern. From it the probable components may be deduced and the number of subsequent patterns needed for complete identification can be greatly reduced. Sometimes an oriented aggregate pattern will give all the information required.

It may be objected that orientation effects make quantitative estimation impossible, but even alleged unoriented specimens of clays are usually partially oriented. Furthermore, the usual method of estimation by comparing the patterns of the unknown with those of standard mineral mixtures is of limited application as it is often uncertain if the

standard minerals and those in the unknown diffract in the same way or even similarly. Quantitative estimation of clay minerals will remain generally impossible until we know more about them.

The chief advantages of the new method are that small amounts of soil can be used and that the whole process takes about 2 hours. In pedology it will enable small, morphologically discrete features to be studied separately. Samples representative of whole horizons have been used previously in mineralogical studies of soils. Soils do not form in the first instance in the broad level horizons so beloved of the soil scientist. In addition horizons are not uniform either laterally or vertically. Soil formation takes place mainly by chemical and physical reactions along planes of weakness in the mass. Features such as root channels and structure faces in soils and joints in rocks are the places where the bulk of altering solutions come into contact with unaltered minerals. The new method will be of greatest value in following the mineralogical changes which occur in these localized centres of soil formation.

The field pedologist today is describing soil profiles in ever greater detail. In the field and the laboratory Kubiena (1938) has made many detailed studies of micromorphology. Meanwhile the soil mineralogist still confines his attention to soil horizons. The method outlined in this paper allows the investigation of less than 0·1 g. soil, an amount that is near the size limit of features that can be seen by the field pedologist. The semi-micro mineralogical approach should help to relate field morphology and mineralogy. Future work using X-ray techniques (Kellar, Hirsch, and Thorp, 1950) at present being used in metallurgy may enable us to relate micromorphology to mineralogy still more closely.

Acknowledgement

I wish to thank Mr. G. C. Dibley for making the centrifuge tubes.

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THE IDENTIFICATION OF MONTMORILLONOIDS IN CLAYS

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Introduction

ALTHOUGH it is fairly simple to detect by X-ray diffraction the presence of montmorillonoids in clays using glycerol (MacEwan, 1944) or ethylene glycol (Bradley, 1945), the specific identification of the members of the group, although desirable, is fraught with difficulty.

In principle it is possible to distinguish between di- and tri-octahedral montmorillonoids from the position of the (*hk*) reflections (MacEwan, 1949), but it is also necessary to know the amount of iron in the mineral before a definite conclusion can be reached (MacEwan, 1951). With the exception of hectorite, most trioctahedral montmorillonoids derive their charge from tetrahedral substitutions and present comparatively little difficulty in their classification. On the other hand, the distinction between dioctahedral montmorillonoids of low iron content is impossible without the complete separation of the montmorillonoid from other minerals, the saturation of the exchange complex with an ion not occurring in the silicate sheet, and subjection of the resultant material to a silicate analysis. The chief objection to this time-consuming procedure, even if it were possible to carry it out in all cases, is that there is no satisfactory method of removing amorphous oxides from the separated clay without releasing more oxides by decomposition of the montmorillonoid. A silicate analysis may be positively misleading unless great precautions are taken.

As a result of dehydration studies on the montmorillonite-beidellite series of minerals (Greene-Kelly, 1952*a*, 1953) it has been possible to devise a simple test which distinguishes montmorillonite from beidellite and nontronite (Greene-Kelly, 1952*b*). The test is described below in detail and its application to soil clays and weathering problems illustrated by a few examples.

Methods of carrying out the Test

The test depends on the fact that montmorillonite alone of the montmorillonoids shows irreversible collapse perpendicular to the plane of the silicate sheets, when its exchange complex is saturated with small ions and the mineral dehydrated by moderate heating. As a result of the comparison of different exchange ions, it has been established that the effect is one which depends on the size of the ions only, and it has been concluded that the irreversibility is a result of the exchange ions moving into the vacant octahedral sites in dioctahedral minerals. If this movement occurs to a sufficient extent, the effective charge on the silicate sheets becomes very low and the mineral reverts to the non-expanding pyrophyllite-type mineral. This loss of expansion has two important

effects. First the total surface area drops to a low value owing to loss of the interlamellar surface, and secondly the apparent exchange capacity is reduced owing to the fixation of the interlamellar ions. Both these effects can be measured easily by a variety of methods and provide a convenient and specific test for montmorillonite.

In practice the test is most easily carried out with lithium as exchange ion owing to the low temperature required for dehydration. Satisfactory saturation can be obtained by three washings of the montmorillonoid with 3 *M*. lithium chloride, the excess salt being removed with warm 90 per cent. alcohol. In this way flakes and powders can be saturated with lithium without the necessity of centrifuging. A final wash with absolute alcohol is desirable to facilitate easy removal of the clay from the glassware after heat treatment. Irreversible effects begin to occur after drying at 120° C., but for most purposes a temperature of about 200° C. is used. This ensures an exchange capacity change from 90 m. equiv./100 g. to about 3 m. equiv./100 g., a marked surface area change as shown by the adsorption of water and polar organic liquids at room temperatures and a complete loss of expanding properties with glycerol at room temperature as shown by X-ray diffraction.

In the examples which follow, X-ray methods have been used exclusively to detect the change in properties. The use of exchange capacity methods, however, should present no difficulties; any standard technique is suitable, but of particular interest is the semi-micro method of distilling a few milligrammes of the ammonium-saturated clay with sodium hydroxide and collecting the distillate in boric acid (Mackenzie, 1952). The loss of surface area to water can be measured by allowing the sample, after heat treatment, to resorb water at a fixed relative humidity. The water taken up can be estimated by weighing, heating curves, or D.T.A. and compared with that of the unheated sample. Owing to the large change observed, the resorption of water need not be carried to equilibrium, which would unduly lengthen the process if it were carried out in the presence of air.

The samples need not be pure montmorillonoids and by the X-ray method the test is applicable as long as the 17·7 kX line is visible, i.e. with samples containing a few per cent. of a montmorillonoid. The other methods require a greater percentage of montmorillonoid. It has been found that satisfactory saturation of montmorillonoids with lithium can be obtained with the technique outlined above even in the presence of soluble salts or sparingly soluble substances such as calcium carbonate.

Scope of the Test

The test has given positive results with many montmorillonites, among them being Wyoming bentonite, Fullers Earth (Redhill), Fullers Earth (Woburn), and Rosedale (Alberta) bentonite. All these minerals gave a rational series of (00*l*) reflections corresponding to *d*(001) of 9·5 kX after heat treatment and soaking in glycerol.

Samples of dioctahedral montmorillonoids containing little magnesium and identified as beidellites and nontronites gave a negative

result with the test. Trioctahedral montmorillonoids also gave a negative result with the test.

In a few cases intermediate behaviour was found resulting in a characteristic increase of central scatter, broadening of the (00*l*) reflections, and their non-rationality. This is normally associated with random interstratification and in this case probably of 9·5 and 17·7 kX (MacEwan, 1949; Brown and MacEwan, 1950). The relative amounts of tetrahedral and octahedral substitution required for this effect are not yet known with certainty. The relative amounts may be approximately equal.

Application of the Test

Black Cotton soil (*Hyderabad, India*)

A clay sample from Profile 7 described in a paper by Nagelschmidt, Desai, and Muir (1940) was examined and found to give no change in properties on lithium saturation and heating. Since analysis of the superfine fraction showed 22·8 per cent. Al_2O_3 and 12·0 per cent. Fe_2O_3 and the clay was composed entirely of a dioctahedral montmorillonoid, it was concluded that the mineral should be classified as a beidellite. This is in agreement with the conclusions of the authors from the comparison of the analysis with that of beidellite from Beidell (Nagelschmidt, 1938). One significant difference between the analyses of the two minerals is the markedly greater MgO content of P7 (1·95 per cent.) as compared with the mineral from Beidell (0·70 per cent.). Since P7 was washed free of calcium with acetic acid and hence was free of exchangeable magnesium, this magnesium is non-exchangeable and should be allocated at least in part to the octahedral layer. This suggests that P7 derives some of the charge on its silicate sheets from octahedral substitutions.

Brown basaltic soil (*Syria*)

The clay samples were from Profile IS17 described in a paper by Muir (1951). The soil is derived from a glassy basalt containing magnesium-bearing minerals. The exchange complex was composed predominantly of calcium and magnesium. The clay fraction contained a montmorillonoid as the predominant mineral. Examination of the clay by the heating test showed no change, and since the mineral was dioctahedral and was not predominantly iron bearing, it was classified as a beidellite. This confirms the author's suggestion. The occurrence of beidellite in a soil derived from a parent material high in magnesium is surprising; it might be expected that either montmorillonite or a trioctahedral montmorillonoid would be formed preferentially.

Clay from weathered mica (*Spiggie, Shetland*)

A clay which proved to be a montmorillonoid was collected and investigated by Dr. I. Stephen. It was formed by the weathering of blocks of compact rock consisting mainly of a fine-grained dioctahedral white mica (sericite), the mica being a secondary after original feldspar. Application of the heating test showed no change. The clay did not

appear to be high in iron and was dioctahedral and could therefore be classified as a beidellite. This result is not unexpected.

Grey wooded soils

The soils from two profiles from Alberta and Saskatchewan had been investigated by Mr. G. Brown and found to contain a predominant amount of a montmorillonoid in the former case throughout the profile, but in the latter case it was concentrated in the B and C horizons. These soils, although resembling podzols, show the unusual feature of a decreasing pH from the A_2 to the B_1 horizon. Examination of the clay from these soils showed them to belong to the intermediate montmorillonite-beidellite group.

Black soils (*Sudan*)

These soils which may have been derived from basalt were found to contain a predominant amount of montmorillonoid which was closely similar to that found in the grey wooded soils.

Black Cotton soil (*Gold Coast*)

This soil has been investigated recently by Dr. I. Stephen (1953). It is derived from a basic gneiss and the clay fraction was found to contain a predominant amount of a montmorillonoid. Application of the heating test showed that it was a typical montmorillonite. This was in agreement with the occurrence of magnesium-bearing minerals in the parent material.

Black Cotton soils (*Kenya*)

These soils occur on the Athi plains. The parent material is an incompletely differentiated volcanic rock of Cretaceous to Recent age, among which phonolites and phonolitic trachytes are prominent. The application of the heating test to the montmorillonoid clay showed that it was a typical montmorillonite.

Altered granite (*Shetland*)

The clay from the altered granite was investigated by Dr. I. Stephen and found to contain a montmorillonoid. Palygorskite was also found associated with the clay. This montmorillonoid was found to be montmorillonite. The exchange complex, in agreement with the occurrence of magnesium-bearing minerals in the clay, was saturated predominately with magnesium and calcium ions. It is clear that the alteration of the granite involved the introduction of magnesium solutions from elsewhere than the parent material.

Conclusion

The examples discussed in the last section indicate the utility of the heating test in classifying montmorillonoids in clays. This may help to elucidate the conditions of formation of the clay mineral.

Where soils contain a large proportion of a montmorillonoid it may be important to decide which member is present. For example, the

occurrence of beidellite in a soil may mean that the soil has a greater potassium-fixing power than a similar soil in which montmorillonite is the predominant clay mineral (Marshall, 1949, p. 126). With a more rigorous classification of soil montmorillonoids other important differences may well become evident.

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PRELIMINARY NOTE ON A SUGGESTED NEW METHOD FOR EXCHANGEABLE BASES IN CALCAREOUS SOILS

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IN numerous soil investigations carried out in these laboratories none of the currently accepted methods of estimating total exchangeable bases in calcareous soils has been found satisfactory. Rice Williams's method (1928) has been used, followed by determination of free carbonates by Collins's calcimeter (1906). This effects complete solution of free carbonates, but complete replacement of exchangeable cations is not always obtained, especially in heavy soils. The method of Bray and Willhite (1929) is preferable in this respect, but is not applicable to calcareous soils, because the ammonium acetate dissolves an unknown and variable proportion of the free carbonates. Hissink's method (1923) is not designed to give total exchangeable bases figures, is based on a doubtful assumption, and is not ideally suited to the routine analysis of a large number of samples.

In this preliminary note a simple modification of the method of Bray and Willhite is presented, which provides in one set of operations reasonably accurate figures for exchange capacity, total exchangeable bases, and free carbonates in calcareous soils. The assumption is made that in such soils the exchange complex is largely, if not entirely saturated, and the exchange capacity is therefore a measure of the total exchangeable bases.

Outline of Procedure

Twenty-five grammes of soil are treated overnight with 100 ml. N/2 acetic acid. (This quantity of acid is twice the stoichiometric amount required to destroy all free carbonates in a soil containing 100 m.e. per cent. When this figure is greatly exceeded it is proposed to use N acetic acid in order to keep the volume to 100 ml.)

The extract is filtered under gentle suction through a Whatman 42 paper into a flask roughly graduated at 400 ml. The soil is then leached with successive small portions of N ammonium acetate (pH 7) until a total of 400 ml. of extract has been collected, when it is transferred to a measuring flask and made up to 500 ml. The soil is then washed with 200 ml. 80 per cent. v/v alcohol, leached by the same technique with 2 per cent. KCl solution and the extract made up to 500 ml.

A suitable aliquot of the acetic acid-ammonium acetate extract is evaporated to dryness, ignited in a muffle furnace at 520° C., taken up with standard HCl overnight, filtered, boiled to expel CO_2, and back-titrated with CO_2-free NaOH. Total exchangeable bases plus bases present as free carbonates are thus obtained.

Exchange capacity is determined on an aliquot of the KCl leachate by distillation with MgO into standard HCl and back titration.

Taking exchange capacity as equal to total exchangeable bases, free carbonates are calculated by difference.

Preliminary Tests on Rhodesian Soils

Five soils were selected for a preliminary test of the method:

112/R/51: Calcareous, light sandy loam.
113/R/51: Similar sandy clay.
124/R/51: Highly calcareous clay.
125/R/51: Similar to 124/R/51.
137/R/51: Non-calcareous, black, heavy clay.

These soils were analysed by the following methods and the results are shown in Table 1:

(1) Total exchangeable bases by acetic acid extraction throughout as in Rice Williams's method, and free carbonates by Collins's calcimeter.
(2) Exchange capacity and total exchangeable bases by the suggested new method, calculating free carbonates by difference.
(3) As (2), but using normal ammonium acetate throughout as in the method of Bray and Willhite.

Finally one calcareous soil (124/R/51) was leached with N ammonium acetate after initial soaking with (*a*) N/2 acetic acid and (*b*) N ammonium acetate, and the pH's of the leachates were determined at successive stages of leaching.

TABLE 1

A. Total exchangeable bases plus free car bonates extracted. B. Exchange capacity C. Free carbonates. All results are in milligram-equivalents per 100 g.

	112/R/51			*113/R/51*			*124/R/51*			*125/R/51*			*137/R/51*		
Method	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
1	67·3	..	53·4	66·7	..	51·2	146·5	..	113·6	130·4	..	106·7	26·6	..	nil
2	68·5	12·9	55·6	67·1	12·0	54·7	148·5	21·0	127·5	132·5	21·0	111·5	39·3	42·8	nil
3	33·0	12·3	..	33·9	10·7	..	51·1	18·1	..	49·3	17·3	..	38·8	42·5	..

TABLE 2

pH of leachates at progressive stages after initial soaking with: (a) acetic acids, (b) ammonium acetate

pH of ammonium acetate used: 7·02

	(*a*)	(*b*)
Filtered supernatant liquid before leaching	4·71	7·62
Ammonium acetate leachate direct from funnel after leaching with:		
50 ml.	6·66	7·59
100 ml.	6·83	7·54
200 ml.	7·00	7·50
300 ml.	7·03	7·48
400 ml.	7·04	7·44

From Table 1 it appears that in the case of calcareous soils so far tested initial treatment with N/2 acetic acid, followed by leaching with N ammonium acetate, removes from the soil more bases than leaching with either of these reagents alone. It seems reasonable to infer that the

suggested method effects complete solution of the free carbonates, while replacing the exchangeable cations more effectively than Rice Williams's method. This is supported by the higher exchange capacities obtained by the suggested method, which also indicates that any initial replacement by hydrogen ions, which may result from the acetic acid treatment, does not appreciably affect subsequent saturation of the exchange complex with ammonium ions.

These higher exchange capacities are explained by:

(*a*) The observation of Kelley and Brown that the cations of free carbonates, brought into solution during leaching, interfere with the replacement of exchangeable cations by ammonium ions. The fact that the pH of the leachate following acetic acid treatment (Table 2) does not rise appreciably above 7 indicates that such interfering cations have been completely removed before leaching with ammonium acetate commences.

(*b*) Liberation of clay occluded by free carbonates.

It is considered that these preliminary tests indicate that the method described is a practical way of determining with reasonable accuracy some of the important chemical characteristics of calcareous soils. The time available necessitated the application of routine technique and limitation in the range of soils examined, but further work is planned when opportunity occurs.

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STUDIES IN PEDOGENESIS IN NEW SOUTH WALES

VI. ON THE CLASSIFICATION OF SOILS SHOWING FEATURES OF PODZOL MORPHOLOGY

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STUDIES in different parts of the world have resulted in the recognition of soils which show certain features of the podzol profile, but differ to varying degrees from the classical 'podzol' of northern and north-central Russia. To these several names have been applied, generally implying variations in the extent of profile development, and commonly using the colour of one or other horizon as a diagnostic character.

Examination of the literature shows that the terms 'podzol' and 'podzolized' have been applied rather loosely and in some cases to describe almost any soil showing visible signs of *apparent* sesquioxide and/or clay migration irrespective of associated profile features. Elsewhere direct comparison with unfamiliar groups has been avoided by classifying all such soils as podzolic soils, and other more precise descriptions in terms of characteristic subdivisions have not been attempted, as in Prescott's outstanding monograph (Prescott, 1931) in which a broad belt of 'podzolic' soil was mapped along the coast and hinterland of eastern Australia.

Field and laboratory studies of podzol-like soils throughout New South Wales during several years have demonstrated the need for their more systematic sub-division and the desirability of clarifying existing nomenclature, which has been emphasized by a consideration of overseas work. In this paper an attempt is made to meet it.

General Terms and Concepts

The term 'podzol' was first used to describe soils showing an ashy-coloured layer immediately beneath an organic topsoil. Its use was then extended by the Russian school of soil scientists to embrace a particular type of profile morphology.

Subsequently it was extended to include profiles which contained a lighter-coloured horizon underlain by one of darker and/or stronger colour. It has generally been implied that for all such profiles the same process (loosely termed podzolization) has been operative, the differences being interpreted as due to differences in degree of 'podzolization'. It is suggested here that this need not be the case, and that a profile showing these two features may also be developed by other processes.

The characteristic features appear through the removal of certain constituents from the topsoil (notably sesquioxides, clay, and humus) with subsequent deposition elsewhere in the profile or loss from the

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solum. In order to understand the wide range of soils possessing these two features in common, it is necessary to consider briefly in turn the processes responsible for their development.

The processes by which sesquioxides of iron and aluminium may be mobilized are as follows:

1. As co-ordination compounds with simple organic acids (Jones and Willcox, 1929; Gallagher, 1942; Gallagher and Walsh, 1943).
2. As negatively charged humus-protected sols (Aarnio, 1913; Deb, 1949).
3. By simple solution at low pH.

Iron may be mobilized also:

4. As organic complexes (Deb, 1949; Bloomfield, 1951).
5. In the reduced state, due to microbiological action under anaerobic conditions (Albrecht, 1941).
6. As a silica-protected sol under neutral to alkaline conditions (Reifenberg, 1938; Barbier, 1938).

Clay differentiation may be due to:

1. Simple mechanical washing down from the upper to the lower horizons.
2. Movement following peptization under the influence of sodium and magnesium (?) (Gedroiz, 1926).
3. Movement as negatively charged humus-protected sol.
4. Increased weathering and resultant clay formation at certain depths (Nikiforoff and Drosdoff, 1943).

Translocation of humus may occur in association with certain of the processes as listed above or independently in the colloidal condition.

The characteristic horizon differentiation under discussion may arise from any of these processes acting together or independently.

In the classical podzol, with its surface layer of acid organic matter and acid mineral horizons, conditions could favour the migration of the sesquioxides as co-ordination compounds with simple organic acids, as negatively charged humus-protected sols, or as organic complexes (processes 1, 2, and 4 respectively). If the temporary occurrence of anaerobic conditions in an otherwise well-aerated soil is sufficient to bring iron into the reduced state (Bloomfield, private communication), iron could also migrate by process 5. Simple solutions at low pH might well lead to migration of aluminium, but it would be uncommon for conditions to be so acid as to mobilize iron also (Schofield, 1946).

Variations in the extent to which these processes have operated may produce a range of soils of characteristic morphology, yet differing sufficiently to warrant division into further groups. The common features of these groups would be:

(*a*) A surface layer of acid organic matter.
(*b*) Migration of iron oxide from the surface horizon and its deposition in the subsoil, which may or may not be accompanied by movement of aluminium oxide.

(*c*) Severe base-unsaturation of the exchange complex throughout the profile with resultant high acidity.

Examination of the literature suggests that soils showing these features fall into five main groups. Following Nikiforoff (1937) these may be divided first into the phanero-podzols (Gr. *phaneros*: visible, evident) and the crypto-podzols (Gr. *kryptos*: secret, hidden). In the crypto-podzols, termed 'brown podzolic soils' or 'concealed podzols' by other workers, the bleached horizon is masked by the high proportion of humus present. Although these soils are common in Wales (Robinson *et al.*, 1949) and not uncommon in Scotland, they are of only restricted occurrence in New South Wales, and further subdivision of the group is not at present suggested.

Numerous soils are described in the literature that could be included amongst the phanero-podzols, but in his valuable comparative study of the soils of three continents Stephens (1950) was able to recognize four main divisions, namely the podzols, grey-brown podzolic soils, red podzolic soils, and yellow podzolic soils. It is suggested here that the nomenclature of these groups would be improved by an extension of Nikiforoff's treatment. The normal podzols could be termed 'nomo-podzols' (Gr. *nomeno*: law, regular). The grey-brown podzolic soils, showing acidification and sesquioxide eluviation to a lesser extent, might logically be called the 'lepto-podzols' (Gr. *leptos*: thin or weak), whilst the red and yellow podzolic soils, which to many observers are the product of more than one soil-forming process, could well be combined in one group termed the 'amphi-podzols'[1] (Gr. *amphi* = amphis: double, doubtful). The use of the colour of the subsoil to distinguish between these two groups has been an unsatisfactory feature in their terminology, since not only red and yellow but intermediate shades occur and not uncommonly grade into each other. The use of 'amphi-podzol' as the name for the group still allows the addition of a component to describe the colour, should this be desired.

There is a further group of podzols in which the presence of a water-table in the profile is a distinguishing feature. It has been suggested earlier (Hallsworth and Costin, 1950) that this group of soils, often termed 'gley podzols' or 'ground-water podzols', is considered more logically with the other water-table soils. The two terms used have not always been taken as synonymous (cf. Nikiforoff, 1937), and it must be recognized that the development of a gley horizon on top of a clayey B horizon will give rise to a profile showing features of a podzol-like morphology, as in the solodic soils described below. Restriction of the term 'gley podzol' to those profiles in which the gley horizon is found below the typical horizons of an otherwise normal podzol profile avoids confusion and allows for a more useful separation of the various groups.

The soil conditions described above would also facilitate the migration of clay as a humus-protected sol, and if this process operates, it could be

[1] If it were ultimately desired to use 'latosol' to describe the ferruginous acid red loams, for which the term 'krasnozem' is used by the present authors, it is suggested that 'lato-podzol' might be used for the red and yellow podsolic soils, to express the intermediate character of the profiles observed.

suggested that in some cases podzols might be found in which a horizon of clay accumulation was present, as well as one of sesquioxide accumulation. There is, however, no reason to postulate that clay migration would take place always to an extent proportionate to that of iron, and the presence or absence of a horizon of clay consequently allows a further subdivision to be made to some of the podzol groups mentioned above.

In contrast, the remaining processes of mobilization listed above would most probably require different soil conditions. Thus the removal of iron as a silica-protected sol under neutral to alkaline conditions (process 6) would hardly be expected to occur under an acid surface litter, whilst the peptization of clay under the influence of sodium and magnesium would appear to require the presence of a higher proportion of these ions than would be expected in the base-unsaturated soils described above. Nevertheless, the importance of this latter process has been widely accepted as a mechanism for clay migration with the production of a bleached horizon a little way below the surface, following the work of Gedroiz (1926), and the solonetzic soils, with their characteristic profile morphology, have been increasingly recognized. These soils show a bleached A_2 horizon overlying a much heavier B horizon, rich in clay but with less obvious sesquioxide accumulation. They can be easily distinguished from the podzols by the lack of an A_0 horizon and by the very characteristic columnar nature of the upper portion of the B horizon. Work in these laboratories has shown that there is in New South Wales a further group of soils showing a bleached horizon, sharply demarcated from a clayey B horizon, which is distinct from either the podzols or the solonetzic soils. These soils, which cover considerable areas of the tablelands and western slopes, lack the organic A_0 horizon and marked sesquioxide accumulation of the podzols, and do not show the characteristic subsoil structure of solonetzic soils. Statistical examination of the results from a range of these soils has shown that the degree of eluviation of the clay is highly significantly correlated with the proportion of (Na+Mg) ions in the exchange complex[1] of the B_2 horizon ($r = 0{\cdot}91$; $P < 0{\cdot}001$).

It is suggested that these soils logically form a separate group, to which the term 'solodic' soils may be applied, in the sense that their morphology and analytical characteristics resemble the solod rather than the podzol.[2] This group would probably include many soils previously described as podzolic by the authors and other Australian workers (Prescott, 1931; Stephens, 1950; Gibbons and Hallsworth, 1951). From inspection of the literature it would probably also include the 'grey wooded soils' and some of the grey-brown and red and yellow podzolic soils of the American classifications.

[1] There is evidence (Simonson, 1949) that in the 'red and yellow podzolic soils' of the American pedologists the clay has not been eluviated from the A to the B horizons, but rather destroyed in the A horizon. The data here show that, whatever the process, the degree of its removal from the A horizon is very closely related to the proportion of Na+Mg on the exchange complex of the B_2 horizon.

[2] Details of the field and laboratory studies on which this separation is based will be published subsequently.

An arrangement of the soils of podzol-like morphology, their subdivisions, and some of their synonyms, are given in Table 1.

TABLE 1

An Arrangement of Soils with Podzol-like Morphology

General characteristics	*Great soil group*	*Subgroups*	*Synonyms*
Soils in which the profile has an A_0 horizon of acid organic matter, a B horizon of ferric oxide accumulation, and is strongly base unsaturated and acid throughout	CRYPTO-PODZOL	Sidero-crypto-podzol Pelo-crypto-podzol	Brown podzolic soil, concealed podzol.
Soils in which the profile has an A_0 horizon of acid organic matter, a bleached A_2 horizon, a B horizon of ferric oxide accumulation, and is strongly base unsaturated and acid throughout	NOMO-PODZOL	Sidero-(nomo-)podzol* Pelo-(nomo)-podzol Organo-(nomo)-podzol Organo-pelo-(nomo)-podzol	Iron podzol Iron podzol with clay B Humus podzol Humus podzol with clay B (The classical podzols of the Russian school.)
	LEPTO-PODZOL	Sidero-lepto-podzol Pelo-lepto-podzol	Some grey-brown podzolic soils.
	AMPHI-PODZOL	Yellow amphi-podzol Red amphi-podzol	Some of the yellowish-brown and reddish-brown lateritic soils of the American classification, and some of the red and yellow podzolic soils of Australia.
Soils in which the profile has an A_0 horizon of acid organic matter, a bleached A_2 horizon, a B horizon of ferric oxide accumulation, and is strongly base unsaturated and acid throughout; with ground-water present below the B horizon for at least part of the year.	GLEY-PODZOL	Sidero-gley-podzol Organo-gley-podzol	Ground-water podzols.
Soils in which the profile has a bleached A_2 horizon, a sharply demarcated clay B horizon, and with the exchangeable cations of the B_2 horizon dominated by sodium and magnesium	SOLOD SOLODIC	Red solodic soil	Some of the red podzolic soils of American and Australian pedologists.
		Brown solodic soil	Some grey-brown podzolic soils of American pedologists.
		Grey-brown solodic soil Grey solodic soil	Some of the grey-brown podzolic soils and yellow podzolic soils of America and the grey wooded soils of Canada.†
	CALCAREOUS SOLODIC	Calcareous red solodic soil Calcareous brown solodic soil	
	SOLODIZED SOLONETZ	Solodized solonetz	Some of the 'magnesium solonetz' of the American and Canadian pedologists.
	SOLONETZ	Non-calcareous solodized solonetz	

* Depending upon the dominant profile feature, the 'thin-iron-pan' soils of Crompton (1952) would be classified with the nomo-podzols or water-table soils.

† The 'alkaline podzols' of Gallagher and Walsh (1942) appear to be related to this group.

The Characteristics of the Soil Groups

If it be accepted that the constant feature of all podzol profiles is the preferential removal and deposition of ferric oxide (with or without aluminium oxide), but that some of them may also show horizons of either clay or humus accumulation, or both, then a logical system for

naming the subgroups can be obtained by the use of the prefixes 'sidero-', 'pelo-', and 'organo-'[1] to denote respectively podzols with zones of ferric iron, clay, and humus; it being understood that pelo- and organo-podzols must also contain a zone of ferric-oxide accumulation.

The distinguishing features of the nomo-podzols are the presence of a well-developed A_0 horizon, or at least a highly organic A_1 horizon, overlying a strongly bleached A_2 horizon. Although strongly demarcated from the B horizon, the actual junction between the two is commonly highly irregular. The B horizon may be either orange, coffee-coloured, or black, depending on the relative abundance of iron oxide and humus. The crypto-, lepto-, and amphi-podzols do not show the same development of the bleached horizon.

In the crypto-podzols the bleaching is masked by the greater quantity and deeper penetration of the organic matter. These soils show highly organic A_0 and A_1 horizons with but little change of colour until the brighter orange tints of the B horizon are encountered. Sesquioxide migrations can be demonstrated by chemical analysis.

The lepto- and amphi-podzols contain less organic matter than the previous two groups in the upper horizons, and the A_0 is commonly poorly developed. The lepto-podzol shows a thin and poorly developed A_0 horizon, overlying a grey to grey-brown, light to medium-textured A_1 horizon. This merges gradually into a lighter coloured, often yellowish, A_2 horizon. This is fairly sharply demarcated from a thin, yellow, orange or red-brown B horizon, sometimes of heavier texture and relatively compact, which grades into the decomposing parent material at lower depths. The profile rarely exceeds 4 ft. in thickness.

The amphi-podzol shows a thin and poorly developed A_0 horizon overlying a grey, grey-brown or brown, light to medium-textured A_1 horizon. This merges gradually into a lighter coloured A_2. By contrast with the lepto-podzols, the B horizon is a bright red or yellow friable and crumbly clay, fairly high in sesquioxides and showing some resemblance to the subsoil of a krasnozem. The solum is usually deep, and the thick B horizon forms the dominant feature.

The other soils to be discussed here which show certain features of podzol-like morphology are all characterized by a light to medium-textured bleached A_2 horizon, often containing a few discrete ferruginous nodules, which is underlain by and sharply demarcated from a much heavier textured and compact B horizon which need not show evidence of sesquioxide accumulation. Analysis of these soils shows that, in contrast to the podzols, the exchangeable bases of the deeper subsoils are always dominated by (sodium + magnesium). The great soil groups and subgroups included under this general description may be separated by concomitant chemical, structural, textural, and colour characteristics.

The solonetz group shows a thin bleached A_2 horizon, overlying a characteristic B horizon of columnar structure, the columns having rounded tops. Hydrogen[2] is either absent or insignificant in the

[1] Gr. *sidero*, iron; pelo(s), clay; organico(s), organic.

[2] Although there is doubt as to whether H ions exist in the exchange complex, the concept is adhered to here for simplicity of presentation.

exchange complex in all horizons, whilst calcium, magnesium, and sodium are all present in roughly similar proportions at the surface, but with sodium and magnesium increasing with depth and becoming co-dominant. Soils of this group have rarely been encountered by the authors.

Numerous soils have been found with the characteristic rounded tops at the junction of the A and B horizons, with a much thicker A horizon (averaging 12 in.) and with an appreciable proportion of H ions on the exchange complex, especially in the A horizons, but with the sodium distinctly lower than in solonetz (analogous to some North American soils—viz. Ellis and Caldwell, 1935). The pH in all cases rises from quite acid at the surface to neutral or alkaline in the B_2. To these soils the term 'solodized-solonetz' has been applied, after Gedroiz (1926). They may be regarded as intermediate between the normal solonetz and the solodic soils.

The solodic soils show a fairly thick bleached A_2 horizon (averaging about 9 in.) but no evidence of the characteristic tops to the B horizon of the solonetz and solodized-solonetz, although some degree of irregularity may be found. The exchange complex carries an appreciable proportion of H ions in the A horizons that decreases in the B horizons. Exchangeable sodium increases in the B horizons to levels below those found in solonetz or solodized-solonetz soils. For New South Wales soils there is always an increase in the proportion of exchangeable magnesium to about 50 per cent. or more in the B_2 horizon. From a moderately acid surface soil the pH usually shows a marked rise with depth.

The solodic soils may be differentiated on the basis of the colour of the A and B horizons into the subgroups red, brown, grey-brown, and grey solodic soils. The grey solodic soils are distinguished from the grey-brown solodic soils mainly by the presence of gleying in the B horizon.

Profiles have also been found which show the morphological features of the solodic soils as described above, but contain also concretionary calcium carbonate in the lower horizons. These have been found either on slightly more basic rocks or in the lower positions of the catena. Their occurrence in these latter situations represents a similar catenary development to that already described for the sequence of soils found on basalt (Hallsworth, Costin, Gibbons, and Robertson, 1952). It is suggested that these calcareous members should logically be considered as a separate group, designated calcareous solodic soils (cf. Profile 334).

The solods have the general morphological characteristics of the grey-brown and grey solodic soils, and may be distinguished at present only on their chemical characteristics. The soils are acid throughout. Exchangeable calcium falls from low in the surface to even lower values in the subsoil. Magnesium and sodium show their customary rise to the B_2 horizon, sodium slightly, magnesium appreciably, but at all levels being completely dominant to calcium.

The differences between the main soil groups are illustrated by the following profile descriptions from New South Wales.

Nomo-podzols

These soils are usually found in moist temperate regions and have been observed, for example, on granite on the montane tract at Kosciusko and on rhyolite at Orange in the Central Tablelands, but are best developed on sand deposits on the coast, on which they extend to sub-tropical latitudes (Simonett, 1949; Maze, 1946). Some soils showing a pelo-podzol profile are found on the central coast where they are probably formed through sand overlying clay, as for instance where a shale lens may be exposed in the Hawkesbury sandstone; and although these are pseudo-profiles, strictly speaking, they are sufficiently common to warrant mention (e.g. Middle Harbour Profile).

Sidero-podzol: Kybean profile

Locality and environment: Kybean Range, 4,000-ft. elevation; steep; excessive drainage; parent material conglomerate; heath vegetation dominated by *Casuarina nana* and *Leptospermum lanigerum*; average annual precipitation about 30 in.

Morphology:

A_0 0″–8″ Brownish mor, consisting of *Casuarina nana* branchlets and moss; clearly demarcated from underlying mineral soil; porous, almost dry; organic carbon 9·7%; pH 4·4; exchange capacity 27·02 m.e., 67·17% base-unsaturated.

A_1 8″–12″ Dark greyish sandy loam, merging with A_2; quartz gravel fairly common; single-grain structure; fine porous and friable; roots moderate in amount; moist; clay 11·3%; organic carbon 1·9%; pH 4·3; exchange capacity 9·34 m.e., 80·94% base-unsaturated.

A_2 12″–16″ Greyish-brown gravelly sand, merging slightly with BC; quartz gravel abundant; single-grain structure; porous and friable, but with harsh feel due to gravel; little humus and few roots; moist; clay 10·6%; organic carbon 1·08%; pH 4·0; exchange capacity 2·36 m.e., 55·5% base-unsaturated; free ferric oxide 0·1%.

BC 16″–20″ Yellowish-grey sandy loam, passing into conglomerate; fragments of parent material fairly common; single-grain structure; fine porous; friable to slightly compact; few roots; moist; slight accumulation of translocated ferric oxide; clay 13·9%; organic carbon 1·2%; pH 4·1; exchange capacity 4·29 m.e., 58·74% base-unsaturated; free ferric oxide 0·2%.

Sidero-podzol: Kosciusko profile

Locality and environment: Montane tract, Kosciusko, 4,230-ft. elevation; steep; free drainage; parent material gneissic granite; wet sclerophyll forest vegetation of *Eucalyptus* species (*E. pauciflora*, *E. Dalrympleana*, *E. delegatensis*); average annual precipitation about 35 in., with moderate but non-persistent winter snow.

Morphology:

A_0 Sparse leaf litter of *Eucalyptus* species and grasses.

A_1 0″–7″ Light grey gritty to sandy loam, merging slightly with A_2; quartz gravel fairly abundant; unstable crumb structure; fairly porous; friable; humus and grass roots moderate in amount; moist; clay 15·8%; organic carbon 2·7%; pH 5·0.

A_2 7″–14″ Light yellowish-grey (almost bleached) coarse gritty loam, merging slightly with B; quartz gravel fairly abundant; structureless; slightly closed, compact; little humus and few grass roots; just moist; clay 14·6%; organic carbon 0·9%; pH 4·9.

B 14″–20″ Dark yellowish very gritty loam, passing into rotten granite below 20 in.; quartz gravel and stones of decomposing granite abundant; structureless; closed, compact to slightly indurated; no visible humus and few roots; moist; clay 16·6%; organic carbon 0·5%; pH 5·1.

Organo-podzol: Sydney profile

Locality and environment: Moore Park, Sydney, about 50 ft. above sea-level; parent material, blown beach sand; scrub formation of white honeysuckle (*Banksia integrifolia*), rough-barked apple (*Angophora bakeri*), and black oak (*Casuarina suberosa*), the latter dominant on dune crests, and the former dominant in corridors. Average annual rainfall 47·5 in.

Morphology:

A_{00}	Recent leaf litter of *Banksia*, *Angophora*, and *Casuarina*.
A_0 0″–1″	Semi-humified litter, laminated.
A_0 1″–2″	Black sandy peat; coarse granular or compact crumb structure; somewhat porous; dry; merging into
A_1 2″–6″	Dark grey peaty sand; very poor crumb to single-grain structure; porous, loose; roots (shrub) present; dry; organic carbon 0·8%; free ferric oxide 0·68%; pH 4·9; merging into
A_2 6″–12″	Light brownish-grey sand; single-grain structure; very porous, loose; fewer roots; dry; merging into
A_2A_3 12″–48″	White sand; single-grain structure, very porous; loose; roots almost absent; dry.
B_1 48″–56″	Coffee-coloured sand; single-grain to massive structure; closed, slightly cemented, hard, not tenacious; roots less frequent; occasional streaks of this material penetrating lower down old root-channels; organic carbon 1·07%; free ferric oxide 3·42%; pH 5·1; merging into
B_2 56″–70″	Medium brown, occasionally mottled with coffee and orange sand; single-grain structure; porous; not cemented except in darker mottlings; roots (tree) more frequent; dry; occasional blotching and streaks of material above; merging into
C 70″	Yellow sand; single-grain structure; somewhat porous and loose; roots infrequent.

Organo-pelo-podzol: Middle Harbour profile

Locality and environment: Middle Harbour, Sydney, about 30 ft. above sea-level; lower catenary position; parent material, Hawkesbury Sandstone colluvium on truncated lateritic clay; dry sclerophyll forest vegetation dominated by *Eucalyptus piperita*, *Casuarina suberosa*, and *Banksia marginata*; average annual rainfall about 49 in.

Morphology:

A_0	Sparse litter of *Eucalyptus* leaves.
A_1 0″–6″	Greyish sandy loam, merging with A_2; a few fragments of decomposing sandstone; single-grain structure; fine porous, fairly loose; roots and humus moderate in amount; moist; clay 9%; organic carbon 0·6%; pH 4·9; free ferric oxide 0·7%.
A_2 6″–15″	Pale greyish-yellow sandy loam, fairly well defined from B_1; fragments of decomposing sandstone fairly common; single-grain structure; fine porous, compact but easily powdering; few roots and very little humus; just moist; pH 5·0.
B_1 15″–27″	Bluish-black sandy clay with yellowish mottle, merging with B_2C; fragments of decomposing sandstone common; semi-prismatic structure; almost closed; tenacious; much humus; slightly damp; clay 40%; organic carbon 1·1%; pH 5·1; free ferric oxide 3·4%.
B_2C 27″–33″	Orange-yellow mottled very sandy clay with abundant decomposing sandstone fragments, passing into rotten rock; semi-prismatic structure; almost close, slightly tenacious; very few roots and little humus; moist; pH 5·0.

Crypto-podzols

The crypto-podzols are usually associated with nomo-podzols under conditions which favour the greater accumulation of organic matter and its incorporation with the mineral soil. They are found generally in

cooler and moister environments, as, for instance, in the montane tract at Kosciusko, and where associated with nomo-podzols they occupy the moister sites.

Sidero-crypto-podzol: Kosciusko profile

Locality and environment: Montane tract, Kosciusko; elevation 4,510 ft., moderate slope, drainage free to slightly impeded; parent rock material, gneissic granite; wet sclerophyll forest vegetation dominated by *Eucalyptus* (*E. delegatensis*, *E. Dalrympleana*, and *E. pauciflora*); average annual precipitation approximately 40 in., with moderate but non-persistent winter snow.

Morphology:

A_0 0″–1″	Brownish, semi-humified leaf litter of *Eucalyptus* species and the grass *Poa caespitosa*, passing into A; damp.
A 1″–7″	Greyish-black sandy loam, merging with B; gravel and biotite fairly common; fine crumb structure; fine to medium porous, friable to mellow; much humus and many grass roots; damp; clay 21%; organic carbon 4·0%; pH 5·3; free ferric oxide 0·9%.
B 7″–15″	Yellowish to yellowish-brown gritty loam, merging with BC; granite stones, gravel and biotite fairly common; almost structureless; almost closed, slightly compact; little humus, but grass roots fairly common; damp; clay 16%; organic carbon 1·0%; pH 5·4; free ferric oxide 0·7%.
BC 15″–28″	Bluish-yellow coarse gritty loam, with slight mottlings below 28 in. due to incipient gleying; granite stones, gravel and biotite abundant; structureless; closed, slightly indurated; no visible humus, a few tree roots; damp; clay 12%; organic carbon 0·6%; pH 5·0; free ferric oxide 1·0%.

Lepto-podzols

Soils of the lepto-podzol group develop under less severe leaching conditions than any other of the podzol soils. This is usually reflected by their occurrence in drier and frequently warmer environments than the nomo-podzols. They may be found on the tableland tract of the Monaro, on the Blue Mountains, and elsewhere.

Sidero-lepto-podzol: Jindabyne profile

Locality and environment: Tableland tract, near Jindabyne; elevation approximately 3,100 ft., gentle slope; parent rock material gneissic granite; savannah woodland vegetation dominated by *Eucalyptus* spp. (*E. pauciflora*, *E. rubida*, *E. stellulata*) with subordinate grasses; average annual precipitation about 24 in., with light winter snow.

Morphology:

A_0	Sparse leaf litter of *Eucalyptus* and grasses.
A_1 0″–9″	Grey-brown loam to sandy loam, merging with A_2; quartz gravel fairly abundant; loose crumb structure to structureless; fine porous, somewhat loose when dry; little humus, but grass roots fairly common; slightly moist; clay 16%; organic carbon 0·5%; pH 6·4.
A_2 9″–22″	Yellowish-grey sandy loam; fairly clearly defined from B_1; quartz gravel fairly abundant; structureless; very fine porous, somewhat harsh when dry; little humus and few grass roots; almost dry; clay 20%; organic carbon 0·2%; pH 6·6; free ferric oxide 1·0%.
B_1 22″–33″	Reddish-yellow silty loam, merging with B_2; quartz gravel and granite stones fairly common, with small quantity of buckshot ironstone; massive; slightly closed, fairly compact; no visible humus, few grass roots; moist; clay 20%; organic carbon 0·1; pH 6·3; free ferric oxide 1·3%.
B_2 33″–40″	Yellowish gravelly loam, passing into rotten granite below 40 in.; quartz gravel and granite stones abundant; with small amount of buckshot ironstone; structureless; closed, compact; no visible humus and few roots; moist; clay 22%; organic carbon 0·1%; pH 6·5; free ferric oxide 1·5%.

Pelo-lepto-podzol: Kurrajong profile

Locality and environment: 1 mile east of Bilpin, west of Kurrajong, elevation approximately 3,500 ft.; shale (non-calcareous); slightly undulating surface of plateau; wet sclerophyll forest of Sydney blue gum (*E. saligna*), white stringybark (*E. scabra*), turpentine (*Syncarpia aurifolia*). Average annual precipitation 47·7 in. with occasional winter snow.

Morphology:

A_0 0″–½″	Leaf litter.
A_1 ½″–6″	Very dark brown silty loam; small cloddy developing to medium cloddy structure with depth; somewhat porous, very friable; roots (grass) abundant at surface, decreasing with depth; moist; organic carbon 7·86%; clay 40%; pH 4·9; free ferric oxide 1·72%; merging gradually into
A_2 6″–15″	Rich brown silty loam, colour becoming lighter with depth; medium cloddy developing to small pyramidal structure with depth; roots frequent; moist; organic carbon 3·65%; clay 53%; pH 4·7; free ferric oxide 2·31%.
B_2 15″–30″	Mottled red, orange, heavy clay with a little grey on structural unit faces; massive to prismatic structure; occasional roots; faces of structural units moist, and becoming increasingly grey with depth; organic carbon 0·37%; pH 4·5; clay 68%; free ferric oxide 2·69%.
C 36″	Decomposing shale, moist and grey on surfaces of fragments.

Amphi-podzols

These soils are formed on a variety of slopes, generally in warmer and moister situations than the nomo-podzols, and on parent materials richer in ferro-magnesian minerals.

Red Amphi-podzol: Orange profile

Locality and environment: Orange, on Central Tablelands; elevation 3,400 ft.; parent rock material syenite; rolling topography, middle and lower catenary positions; original vegetation sclerophyll forest of mountain-gum (candle-gum) (*E. rubida*), red stringybark (*E. macrorhyncha*), &c., now cleared for grazing. Average annual precipitation 34·5 in. with light winter snow.

Morphology:

A_0 0″–¼″	Mass of grass roots.
A_1 ¼″–3″	Grey-brown fine sandy loam; poor crumb structure; porous, friable; grass roots abundant; moist; organic carbon 1·81%; clay 25%; pH 5·4; free ferric oxide 3·87%; merging into
A_2 3″–12″	Grey sandy loam; very poor crumb structure; porous, loose; roots present; moist; organic carbon 1·56%; clay 19%; pH 5·6; free ferric oxide 2·63%; sharply defined from
B_1 12″–48″	Red-brown clay; good crumb structure; porous, friable; roots few; moist; organic carbon 0·53%; clay 53%; pH 5·9; free ferric oxide 5·55%; merging into
B_2 48″–72″	Mottled grey and red-brown sandy clay; massive structure; closed, compact; occasional tree roots; moist; organic carbon 0·25%; clay 43%; pH 5·6; free ferric oxide 5·07%; merging into decomposing parent material.

Solodic soils

These soils appear to be widely distributed over the slopes and tablelands and have been described previously as 'podzolic' soils, and in some cases as 'grey-brown podzolic' soils.

Red Solodic Soil: Gunning profile (*Profile 706*)

Locality and environment: 2 miles south of Gunning, Southern Tablelands. Granite; rolling upper slopes; originally dry sclerophyll forest of red-gum (*E. dealbata* = *E. blakelyi*), mountain oak (*Casuarina stricta*), occasionally Kurrajong (*Brachychiton populneum*), now a cleared grazing paddock. 24·6 in. average annual rainfall.

Morphology:

A_1 0″–3″ Light brown sandy loam; poor crumb to single-grain structure; porous, friable; grass roots in occasional mattes; moist; much grit; organic carbon 1·34%; clay 11%; pH 5·1; free ferric oxide 0·04%, merging[1] into

A_2 3″–12″ Light grey-brown gritty silty sand; single-grain structure; porous hard; grass roots infrequent; slightly moist; much grit; clay 18%; pH 5·1; free ferric oxide 0·16%.

B_1 12″–24″ Orange to reddish-brown gritty sandy clay; compact nutty to massive structure; closed, hard; roots not encountered; dry; much grit; clay 38%; pH 4·7; free ferric oxide 0·22%; merging into

B_2 24″–30″ Mottled brown, orange, yellow gravelly sandy clay; massive structure; closed, hard; dry; clay 29%; pH 4·7; this merges into decomposing parent material.

Brown Solodic Soil: Keira profile (*Profile 334*)

Locality and environment: Keira, 20 miles east of Bingara on Bundarra road, on north-west slopes. Shale (non-calcareous); rolling, lower slopes; originally savannah woodland of red-gum (*E. dealbata* = *E. blakelyi*), stringybark (*E. caliginosa*), occasional ironbark (*E. caleyi*), now partly cleared for grazing. 27·0 in. average annual rainfall.

Morphology:

A_1 0″–3″ Light brown gritty loam; very poor crumb to single-grain structure; slightly porous, friable but hard; grass roots in occasional matte; dry; some grit; clay 34%; pH 5·5; merging into

A_2 3″–21″ Light grey gritty fine sand; single-grain structure; closed, hard, powdery when crushed; grass roots infrequent; dry; some shale pebbles and some ironstone nodules, especially towards bottom of horizon; clay 31%; pH 6·1.

B_1 21″–36″ Dull rich brown clay; massive structure; closed, very compact; roots not encountered; dry; clay 70%; pH 7·0; free ferric oxide 1·57%; merging into

B_2 36″–62″ Yellow-brown (slightly mottled) clay; massive structure; closed, compact but slightly more friable than B_1; roots absent; dry; flecks of carbonate present from 36″ onwards; clay 69%; pH 7·6.

C 62″ Decomposing shale.

Grey-Brown Solodic Soil: Gunning profile

Locality and environment: As for Profile 706 except that this is the bottom catena member.

Morphology:

A_1 0″–5″ Greyish-brown slightly gritty silty loam; poor crumb structure; porous, loose; grass roots frequent; moist at surface (recent rain); organic carbon 1·03%; clay 18%; pH 5·7; free ferric oxide 0·11%; merging into

A_2 5″–12″ Very light brownish-grey silty sand; colour lightening towards 12 in.; single-grain structure; porous, hard, powdery when crushed; grass roots diminishing; dry; numerous ironstone nodules, especially towards bottom of horizon; clay 16%; pH 6·1; free ferric oxide 0·06%.

B_1 12″–36″ Mottled brown, orange, and yellow clay; massive structure; closed, very compact; grass roots few; dry; occasional ironstone nodules

[1] Free ferric oxide figures are for fine earth (< 2 mm.) only, and do not include sesquioxide nodules.

embedded in the top 1–2 in. of this horizon; clay 59%; pH 5·6; free ferric oxide 0·77%; merging into

B_2 36″–54″ Mottled orange, light brown and yellow, slightly gritty sandy clay; massive structure; closed, hard, brittle; no roots encountered; dry; clay 32%; pH 7·2; free ferric oxide 0·24%.

Grey Solodic Soil: Uralla profile

Locality and environment: Kootingal, south of Uralla, on Northern Tablelands; granite; rolling, base of catena; sparse savannah woodland of apple (*E. bridgesiana*), peppermint (*E. radiata*), and stringybark (*E. youmani* and *E. cyathiformis*) with abundant grass of *Aristida* and *Bothriochloa* spp. Average annual rainfall 30·9 in.

Morphology:

A_1 0″–4″ Dark grey gritty coarse sand; fine crumb structure; very porous, loose; grass roots abundant; moist; clay 10%; pH 7·20; free ferric oxide 0·05%; merging into

A_2 4″–9″ Grey gritty coarse sand; poor fine crumb structure; porous, loose; grass roots frequent; moist; clay 11%; pH 7·1; free ferric oxide 0·02%; merging into

A_3 9″–13″ Very light grey gritty sand; single-grain structure; porous, loose, and powdery; grass roots infrequent; moist; nodules of ironstone present; clay 11%; pH 7·1; free ferric oxide 0·02%.

B_1 14″–42″ Mottled grey, brown, and purple gritty clay; massive structure; occasionally semi-columnar where drier; closed, stiff and tenacious; roots not encountered; drier; clay 41%; pH 7·4; free ferric oxide 0·04%; merging into

B_2 42″–72″ Mottled yellow and brown gritty sandy clay; massive structure; finely porous, compact; roots not encountered; merging into decomposing granite at 72 in. Clay 31%; pH 7·7; free ferric oxide 0·12%.

Solod[1]

The solod to date has only been observed by the authors on the more acid rocks of the tablelands and occurs only in small pockets.

Narrangullen profile

Locality and environment: Narrangullen, 23 miles south-west of Yass, on Southern Tablelands. Rhyolite; rolling, base of catena; originally savannah woodland of red gum (*E. dealbata*) and red stringybark (*E. macrorhyncha*) now a partially cleared grazing paddock. Average annual rainfall 24·8 in.

Morphology:

A_1 0″–3″ Light brownish-grey silty clay loam; compact, poor crumb structure; somewhat porous; grass roots present; moist; organic carbon 1·40%; clay 24%; pH 5·0; free ferric oxide 0·52%; merging into

A_2 3″–12″ Light grey, slightly yellowish, silty clay loam; compact, poor crumb to single-grain structure; somewhat porous; grass roots present; moist; organic carbon 0·52%; clay 28%; pH 5·2; free ferric oxide 0·51%.

B_1 12″–18″ Mottled orange and grey clay; compact, nutty to massive structure; closed, tenacious; roots infrequent; almost dry; organic carbon 0·46%; clay 70%; pH 4·9; free ferric oxide 2·04%; merging into

BC 18″–36″ Orange gritty and stony clay; massive structure; closed, less tenacious; roots absent; almost dry; grit and stones of decomposing parent material; organic carbon 0·47%; clay 65%; pH 4·7; free ferric oxide 2·31%.

Discussion

The more precise specification of the profile features of each of the groups and sub-groups of the soils with podzol-like morphology has

[1] Description and analytical data by M. Churchward.

certain implications. The first effect is to reduce considerably the area of soils in New South Wales to which the term 'podzol' or 'podzolic' may be applied. The second is to clarify the relationships of the groups of podzols between themselves and with their environment.

Thus the nomo-podzols occur over a wide rainfall range, as the product of acid leaching under the influence of a mor A_0 horizon, on base-deficient and usually coarse-textured parent materials, a conclusion supported by more recent observations in the British Isles and Europe. This is shown by their typical occurrence in New South Wales on granite in the montane tract at Kosciusko, coarse conglomerate at Kybean, and blown sand along the coast, and in Britain on blown sands in Lancashire (Crompton, 1952) and on sands and gravels in Teindland State Forest (Muir, 1934).

Under drier or warmer conditions, resulting in a smaller accumulation of organic matter, the nomo-podzols are replaced by the less leached lepto-podzols. A parent material of slightly finer texture or higher base status may produce a similar effect in a climate where coarser textured rocks give rise to nomo-podzols.

When the production of organic matter is increased by more favourable conditions of soil moisture, or its destruction restricted by lower temperatures, the nomo-podzols are replaced by crypto-podzols. These conditions may be achieved as climatic or topographic effects.

The vigorous leaching conditions which produce nomo-podzols on acid and coarse-textured parent materials give rise to amphi-podzols on rocks richer in ferro-magnesian minerals.

The thick B horizon of the amphi-podzols, rich in clay and sesquioxide, contrasts markedly with the smaller dimensions of the A horizon. It is difficult to imagine that this clay has arisen largely by eluviation, and it seems much more probable that a considerable part has been formed by weathering *in situ*. This is supported by the similarity shown to the subsoil of the krasnozems, which are the soils forming on fine textured rocks, rich in ferro-magnesian minerals, under similar conditions of rainfall and temperature.

Unlike the podzols, for which a texturally differentiated profile is not essential, the solodic soils are strongly differentiated with respect to clay. This heavier subsoil is not strongly base-unsaturated; on the contrary it contains appreciable amounts of exchangeable sodium and magnesium, and it appears that the translocation of clay has taken place under the peptizing influence of these cations, without a concomitant ferric oxide migration. The bleaching of the A_2 horizons of the solodic soils appears to be a consequence of the development of the clay B horizon, and the extent of bleaching is associated with the sharpness of the boundary and the rate of increase of clay from A_2 to B horizon. The sharpness of increase of clay has been found to be significantly correlated with those changes in climate and topography that are associated with the amount of moisture in the soil. This suggests that the development of the bleached horizon is associated with periodic development of a water-table perched on top of the B horizon. The profiles described earlier for the grey-brown solodic soils with a pale grey horizon passing sharply

into a mottled yellow/brown/grey prismatic structured clay, show obvious similarities to the description quoted by Crompton (1952) for the 'yellow podzolic' soils of Australia. The writers would agree with his interpretation of their genesis, and would suggest that many of the Australian soils at present classed as red and yellow podzolic soils may belong to the solodic group.

The possibility that a podzol-like morphology could arise by more than one process has been considered by earlier workers (e.g. Nikiforoff, 1937; Nikiforoff and Drosdoff, 1943), and the assumption or proof that it can raises a further issue in the classification of such soils. The morphological characteristics of a pelo-lepto-podzol profile seem so close to those of the brown, grey-brown, and grey solodics that the introduction of a fresh group may appear unwarranted. The considerable differences shown in the chemical characteristics, notably the higher figures for exchangeable Na+Mg, the higher pH, and the not infrequent occurrence of secondary carbonate concretions in the B and C horizons of profiles in the lower catenary positions, however, imply, in the authors' opinion, a sufficient divergence from the commonly accepted idea of a podzol as to justify this course.

While it is not known whether similar processes have operated to produce some or all of the so-called 'podzolic' and grey wooded soils described by the North American writers, much of the analytical data available in the literature suggests that this is so.

Summary

The soils which exhibit some features of podzol morphology may be divided into two broad groups, the podzols and the solodic and related soils.

The common features of the podzols are a surface layer of acid organic matter, translocation of iron oxide from topsoil to subsoil, and strong base-unsaturation of the exchange complex throughout the profile with resultant high acidity. The podzols have been divided into crypto-, nomo-, lepto-, and amphi-podzols, and these great soil groups may be divided further according to the character of the clay and humus profiles.

The solodic soils lack the A_0 typical of the podzols and are characterized by a horizon of clay accumulated in the deeper layers, of which the exchange complex is always dominated by sodium and magnesium. Further division into subgroups is made according to colour. The position of these soils with respect to solods, solodized solonetz, and solonetz is also indicated.

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